

# P&S Processing-in-Memory

Real-World Processing-in-Memory Architectures:  
Microbenchmarking of UPMEM PIM

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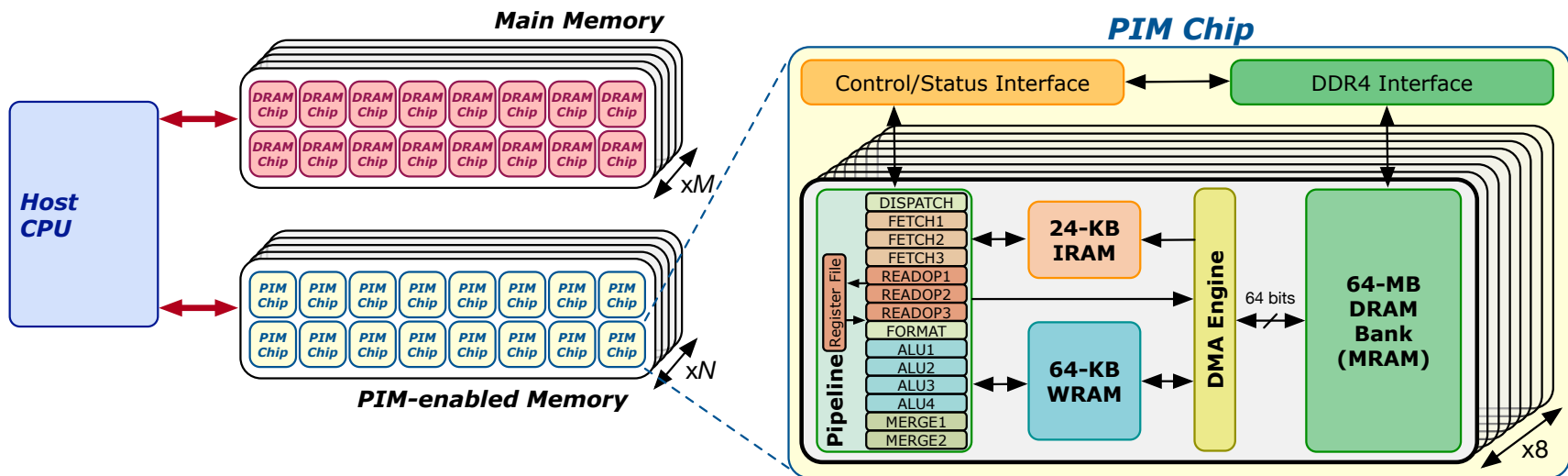
# UPMEM Processing-in-DRAM Engine (2019)

- **Processing in DRAM Engine**
- Includes **standard DIMM modules**, with a **large number of DPU processors** combined with DRAM chips.
- Replaces **standard DIMMs**
  - DDR4 R-DIMM modules
    - 8GB+128 DPUs (16 PIM chips)
    - Standard 2x-nm DRAM process
  - **Large amounts of** compute & memory bandwidth



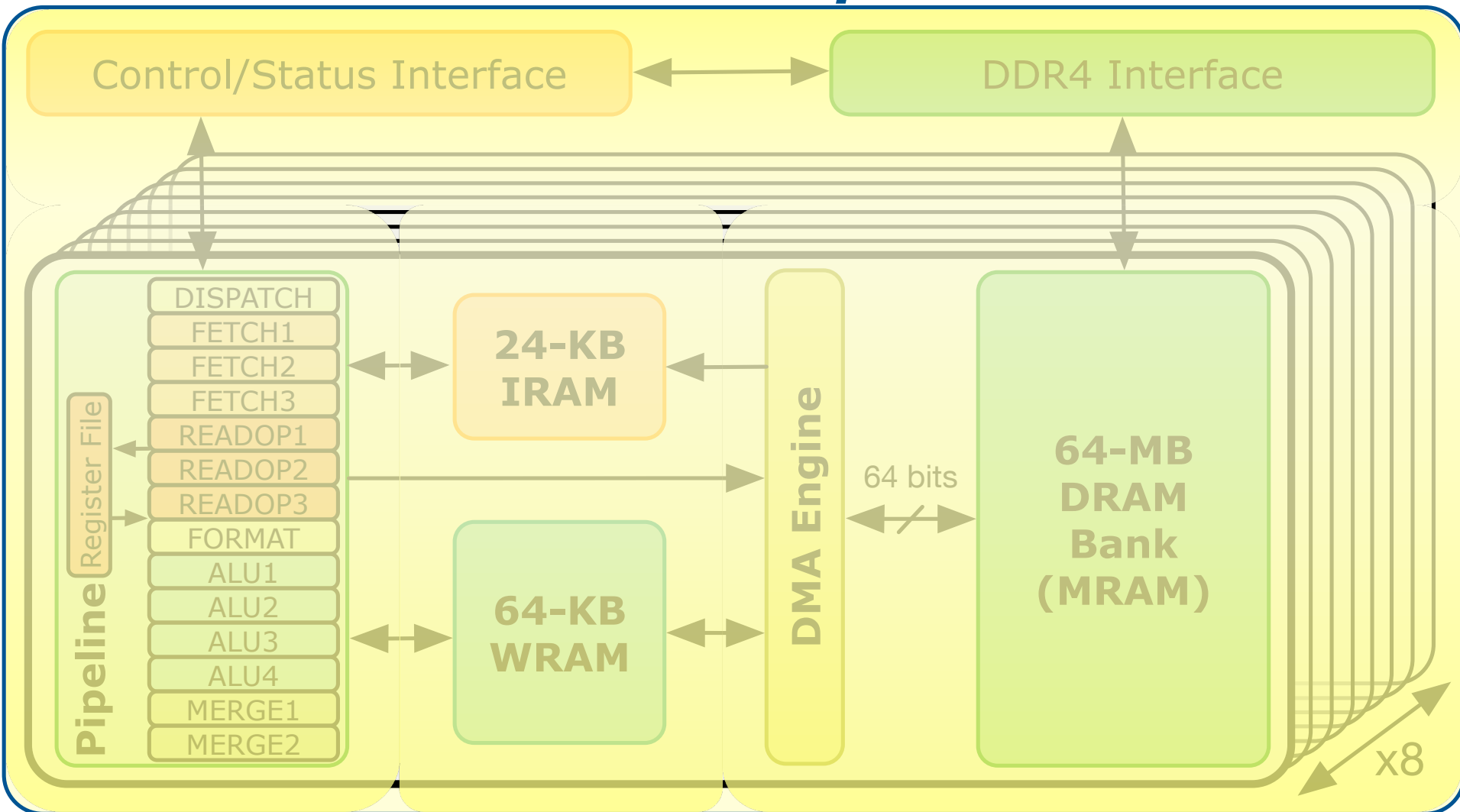
# System Organization

- A UPMEM DIMM contains 8 or 16 chips
  - Thus, 1 or 2 ranks of 8 chips each
- Inside each PIM chip there are:
  - 8 64MB banks per chip: Main RAM (MRAM) banks
  - 8 DRAM Processing Units (DPUs) in each chip, 64 DPUs per rank



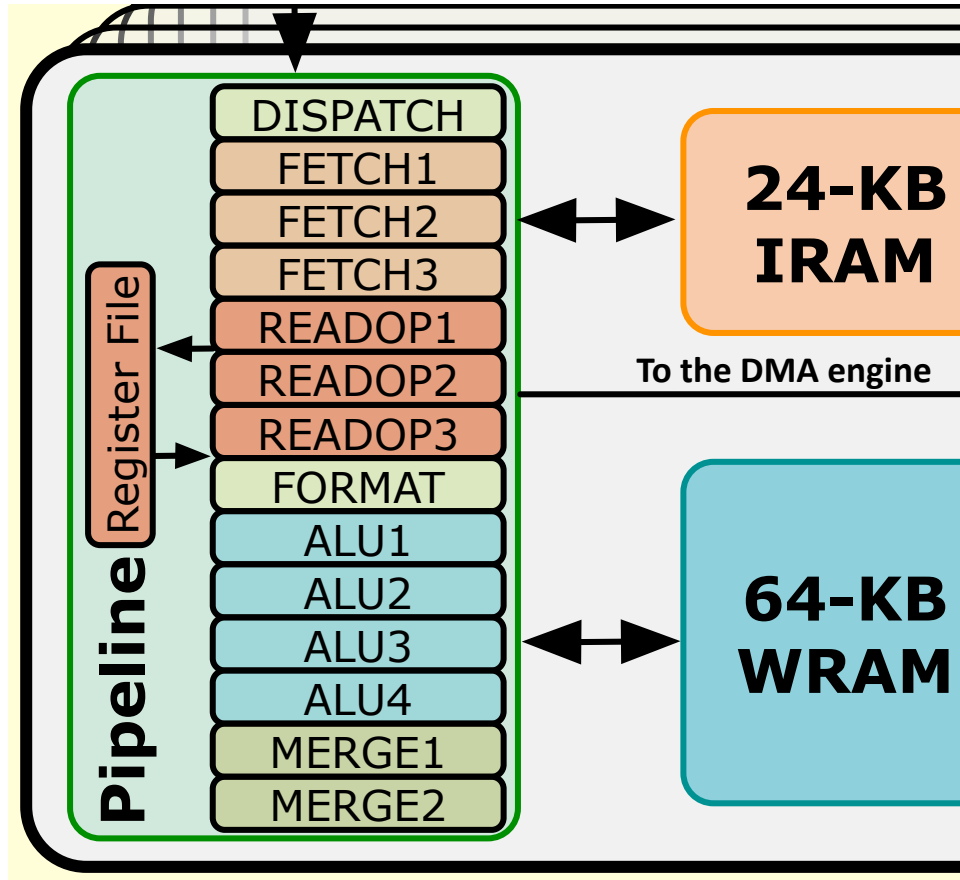
# DRAM Processing Unit

## *PIM Chip*



# DPU Pipeline

- In-order pipeline
  - Up to 425 MHz\*
- Fine-grain multithreaded
  - 24 hardware threads
- 14 pipeline stages
  - **DISPATCH**: Thread selection
  - **FETCH**: Instruction fetch
  - **READOP**: Register file
  - **FORMAT**: Operand formatting
  - **ALU**: Operation and WRAM
  - **MERGE**: Result formatting



\* 350 MHz in the UPMEM-based PIM system used for the experimental results shown in this lecture

# DPU Instruction Set Architecture

- Specific 32-bit ISA
  - Aiming at scalar, in-order, and multithreaded implementation
  - Allowing compilation of 64-bit C code
  - LLVM/Clang compiler

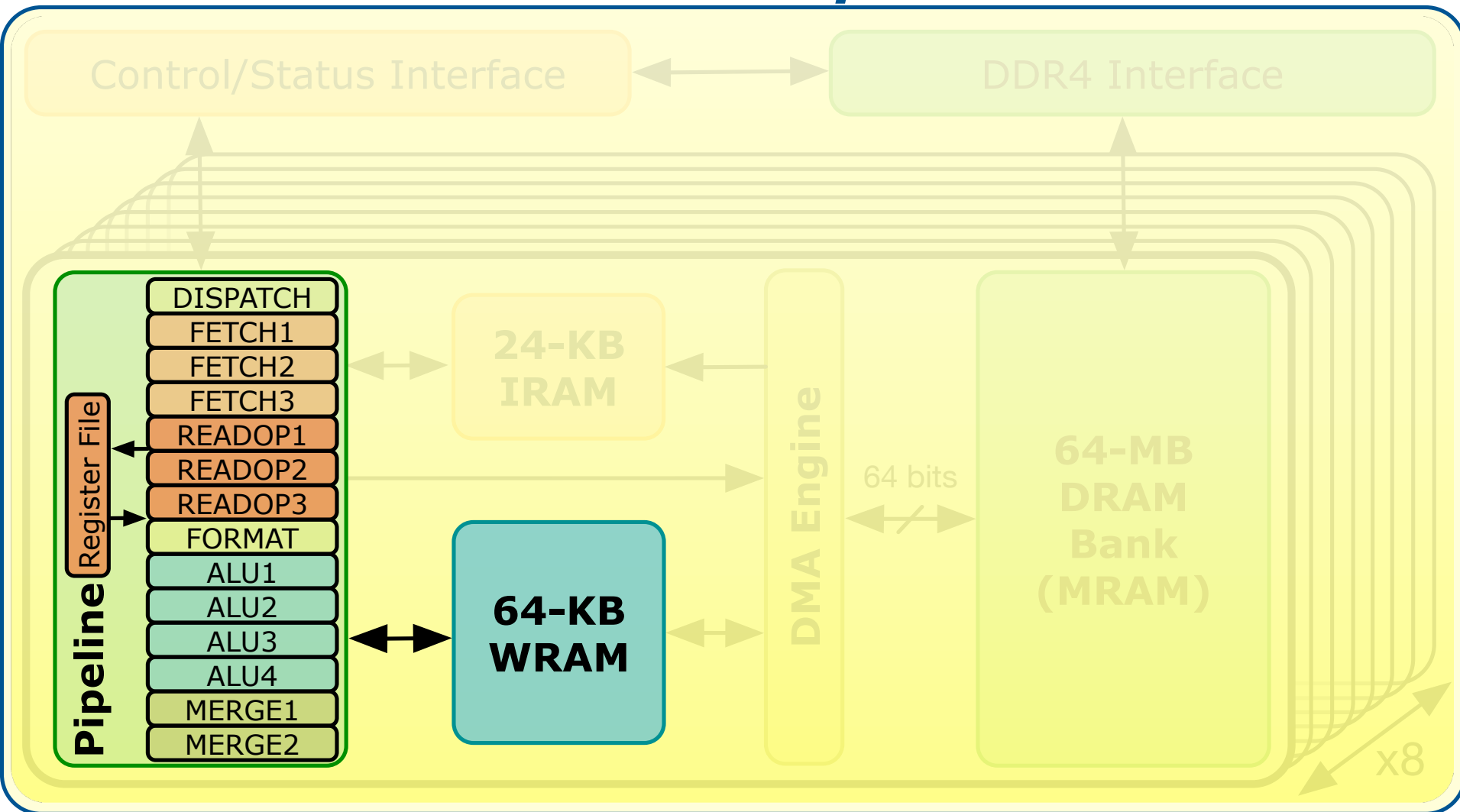
The screenshot shows a web page titled "Instruction Set Architecture" from the "UPMEM development tools documentation". The page has a blue header with a hamburger menu icon and the title "UPMEM development tools documentation". Below the header, there is a breadcrumb trail "» Instruction Set Architecture" and a link "View page source". The main content area has a heading "Instruction Set Architecture" followed by a paragraph: "This section covers the architecture concepts required to understand and use UPMEM DPU processor as a software developer. It is also providing an exhaustive list of the available processor instructions." Below this is another paragraph: "Software developers should use this section as a reference manual to develop or debug assembly code." The next section is "Resources overview" followed by "Thread registers". The text under "Thread registers" says: "The system is composed of 24 hardware threads. Each of them owns a set of private resources:". This is followed by a bulleted list: "• 24 general purpose 32-bits registers named `r0` through `r23`", "• A 16-bits wide program counter, named PC. Notice that the PC value does not address an instruction in memory, but the index of such an instruction directly. For example, a PC equal to 1 represents the second instruction in the DPU's program memory.", and "• Two persistent flags, keeping information about the previous result of an arithmetic or logical instruction:", with a sub-bullet "◦ ZF: last result is equal to zero".

[https://sdk.upmem.com/2021.2.0/201\\_IS.html#](https://sdk.upmem.com/2021.2.0/201_IS.html#)

# Microbenchmarking the UPMEM PIM Architecture

# DPU: Arithmetic Throughput

## *PIM Chip*





# Arithmetic Throughput: Microbenchmark

---

- Goal
  - Measure the maximum arithmetic throughput for different datatypes and operations
- Microbenchmark
  - We stream over an array in WRAM and perform read-modify-write operations
  - Experiments on one DPU
  - We vary the number of tasklets from 1 to 24
  - Arithmetic operations: add, subtract, multiply, divide
  - Datatypes: int32, int64, float, double
- We measure cycles with an accurate cycle counter that the SDK provides
  - We include WRAM accesses (including address calculation) and arithmetic operation

# Microbenchmark for INT32 ADD Throughput

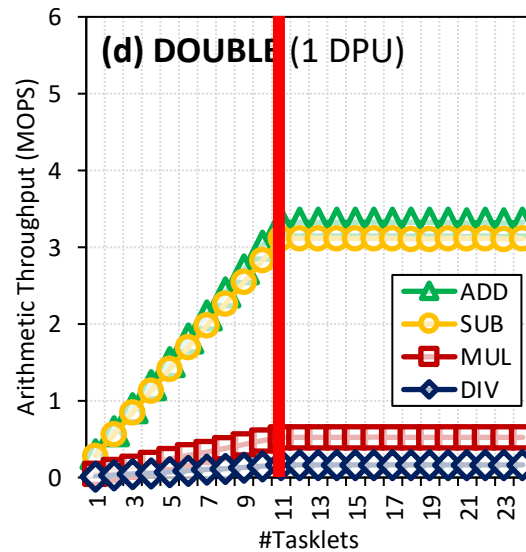
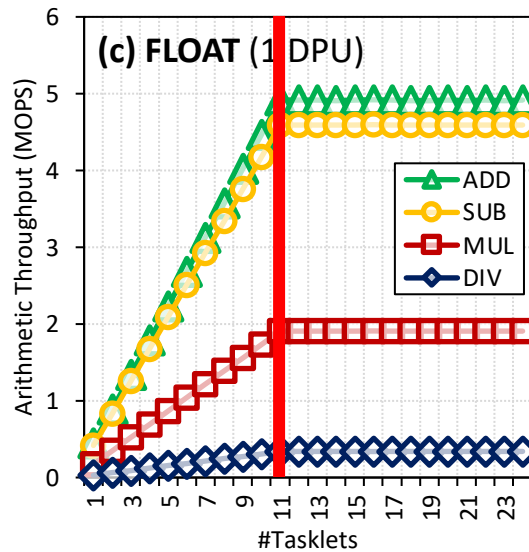
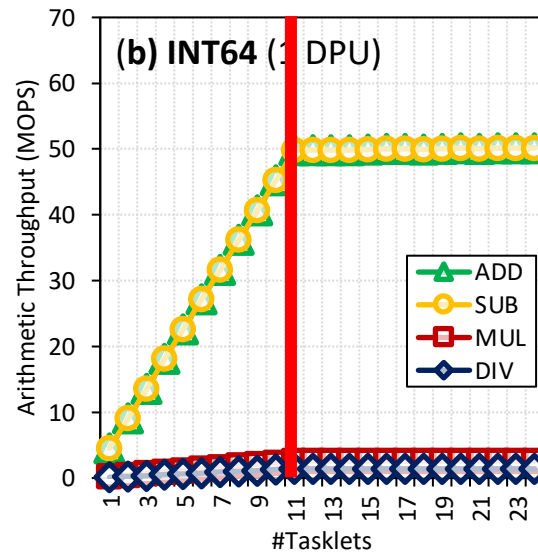
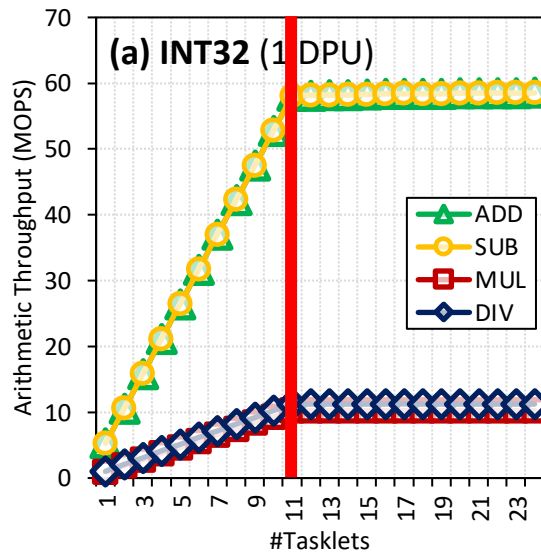
C-based code

```
1  #define SIZE 256
2  int* bufferA = mem_alloc(SIZE * sizeof(int));
3  for(int i = 0; i < SIZE; i++){
4      int temp = bufferA[i];
5      temp += scalar;
6      bufferA[i] = temp;
7  }
```

Compiled code  
(UPMEM DPU ISA)

```
1  move r2, 0
2  .LBB0_1:                                // Loop header
3  lsl_add r3, r0, r2, 2                    // Address calculation
4  lw r4, r3, 0                            // Load from WRAM
5  add r4, r4, r1                          // Add
6  sw r3, 0, r4                            // Store to WRAM
7  add r2, r2, 1                           // Index update
8  jneq r2, 256, .LBB0_1                  // Conditional jump
```

# Arithmetic Throughput: 11 Tasklets

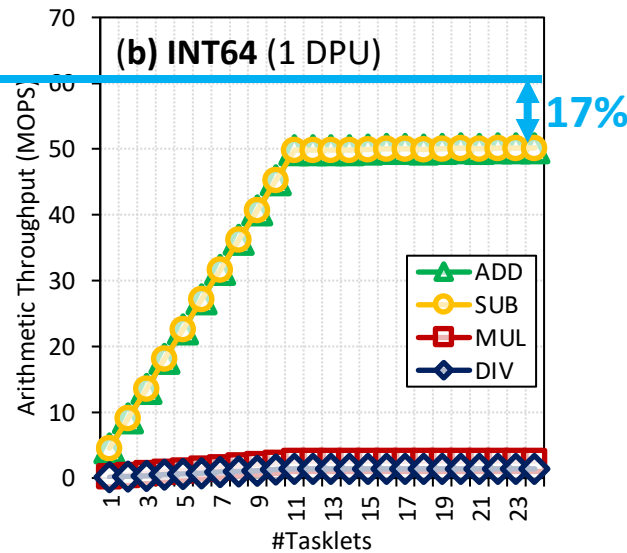
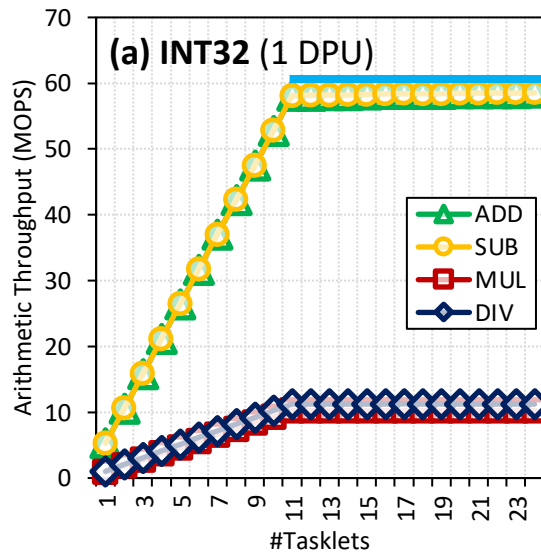


## KEY OBSERVATION 1

**The arithmetic throughput of a DRAM Processing Unit saturates at 11 or more tasklets.**

This observation is consistent for different datatypes (INT32, INT64, UINT32, UINT64, FLOAT, DOUBLE) and operations (ADD, SUB, MUL, DIV).

# Arithmetic Throughput: ADD/SUB



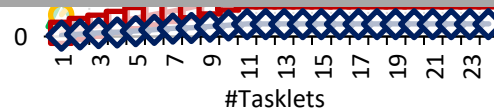
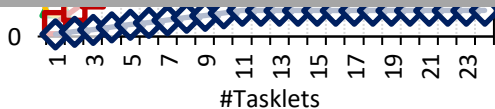
INT32 ADD/SUB are  
17% faster than  
INT64 ADD/SUB

Can we explain the peak throughput?

Peak throughput at 11 tasklets.

One instruction retires every cycle when the pipeline is full

$$\text{Arithmetic Throughput (in OPS)} = \frac{\text{frequency}_{\text{DPU}}}{\#instructions}$$



# Arithmetic Throughput: #Instructions

- Compiler explorer: <https://dpu.dev>

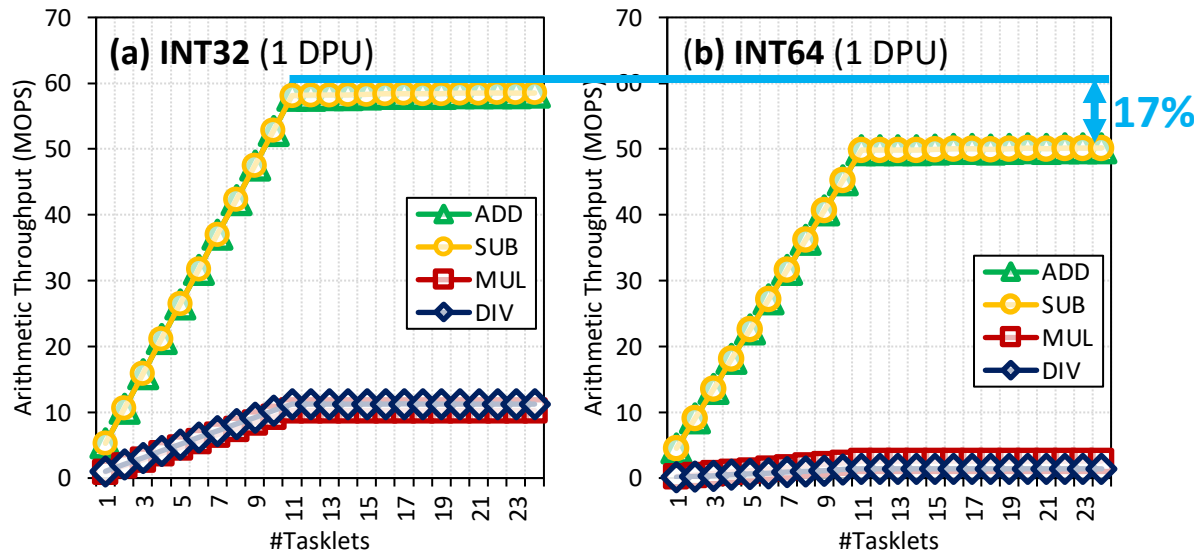
```
1  #define BLOCK_SIZE 1024
2
3  typedef int T;
4  void Benchmark__32bits(T *cache_A, T scalar) {
5      for (int i = 0; i < BLOCK_SIZE / sizeof(T); i++){
6          // WRAM READ
7          T temp = cache_A[i];
8
9          temp += scalar; // ADD
10
11         // WRAM WRITE
12         cache_A[i] = temp;
13     }
14 }
15
16 typedef long T_long;
17 void Benchmark__64bits(T_long *cache_A, T_long scalar) {
18     for (int i = 0; i < BLOCK_SIZE / sizeof(T_long); i++){
19         // WRAM READ
20         T_long temp = cache_A[i];
21
22         temp += scalar; // ADD
23     }
24
25
26
27
```

A ▾ ☐ 11010 ☐ ./a.out ☒ .LX0: ☒ .text ☒ // ☐ \

```
1 Benchmark__32bits:
2     move r2, 0
3 .LBB0_1:
4     lsl_add r3, r0, r2, 2
5     lw r4, r3, 0
6     add r4, r4, r1
7     sw r3, 0, r4
8     add r2, r2, 1
9     jneq r2, 256, .LBB0_1
10    jump r23
11 Benchmark__64bits:
12     move r1, 0
13 .LBB1_1:
14     lsl_add r4, r0, r1, 3
15     ld d6, r4, 0
16     add r7, r7, r3
17     addc r6, r6, r2
18     sd r4, 0, d6
19     add r1, r1, 1
20     jneq r1, 128, .LBB1_1
21    jump r23
```

6 instructions in the 32-bit ADD/SUB microbenchmark  
7 instructions in the 64-bit ADD/SUB microbenchmark

# Arithmetic Throughput: ADD/SUB



INT32 ADD/SUB are  
17% faster than  
INT64 ADD/SUB

Can we explain the peak throughput?

Peak throughput at 11 tasklets.

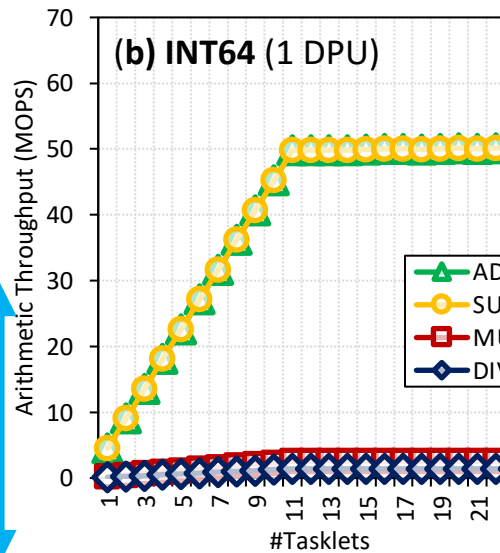
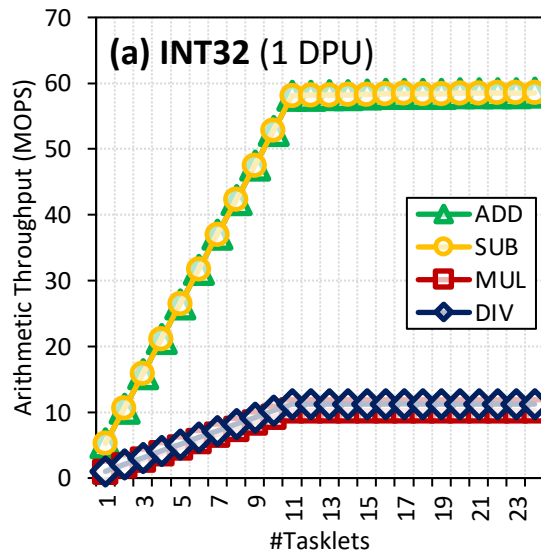
One instruction retires every cycle when the pipeline is full

$$\text{Arithmetic Throughput (in OPS)} = \frac{\text{frequency}_{DPU}}{\#instructions}$$

64-bit ADD/SUB: 7 instructions  $\rightarrow$  50.00 MOPS

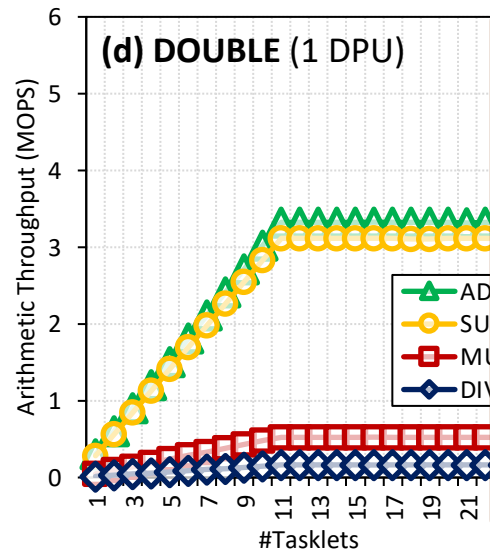
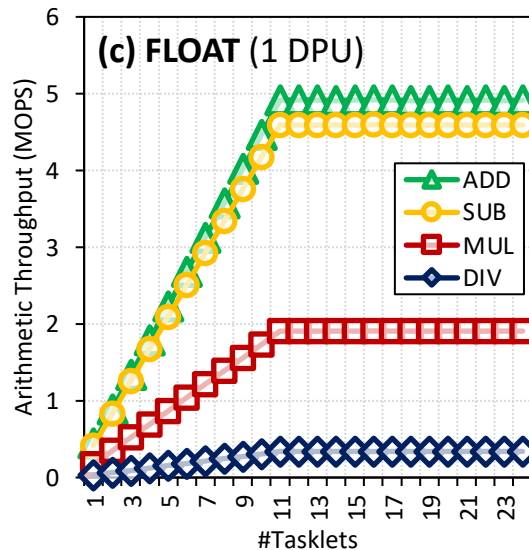
at  $\text{frequency}_{DPU} = 350 \text{ MHz}$

# Arithmetic Throughput: MUL/DIV



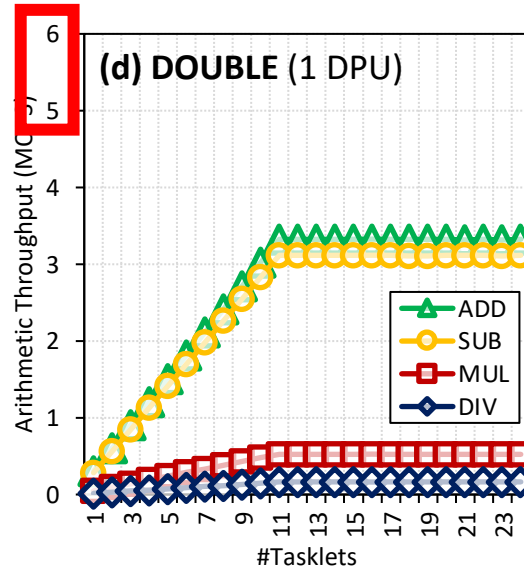
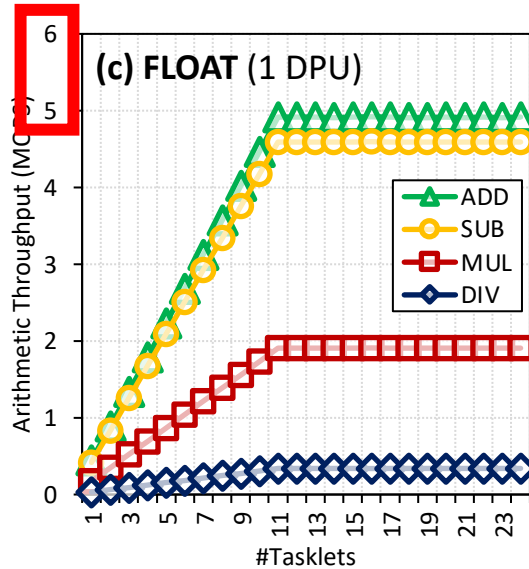
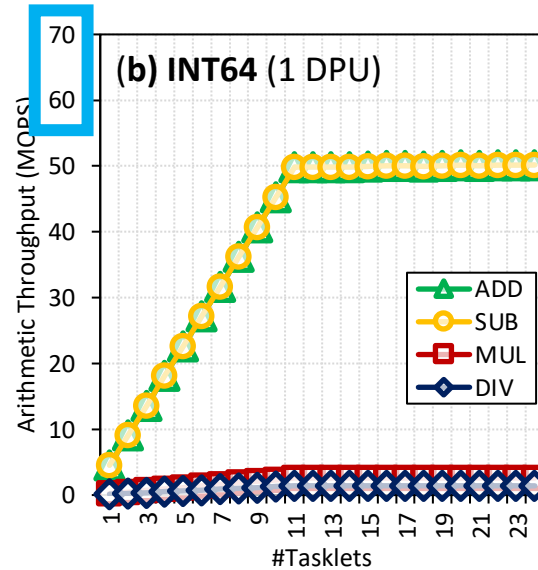
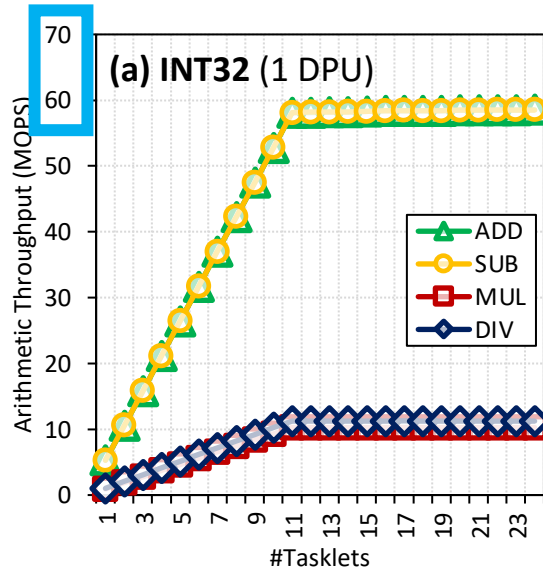
Huge throughput difference between ADD/SUB and MUL/DIV

DPU's do *not* have a 32-bit multiplier



MUL/DIV implementation is based on an instruction that performs *bit shifting and addition* in 1 cycle (MUL/DIV take a maximum of 32 instructions)

# Arithmetic Throughput: Native Support



## KEY OBSERVATION 2

- DPUs provide **native hardware support for 32- and 64-bit integer addition and subtraction**, leading to high throughput for these operations.
- DPUs do ***not* natively support 32- and 64-bit multiplication and division, and floating point operations**. These operations are **emulated by the UPMEM runtime library**, leading to much lower throughput.



# Microbenchmark: Arithmetic Throughput

- Arithmetic throughput for different operations and datatypes

CMU-SAFARI / prim-benchmarks

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2

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Juan Gomez Luna PRIM -- first commit

3de4b49 9 days ago History

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dpu

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9 days ago

folder

host

PRIM -- first commit

9 days ago

folder

support

PRIM -- first commit

9 days ago

file

Makefile

PRIM -- first commit

9 days ago

file

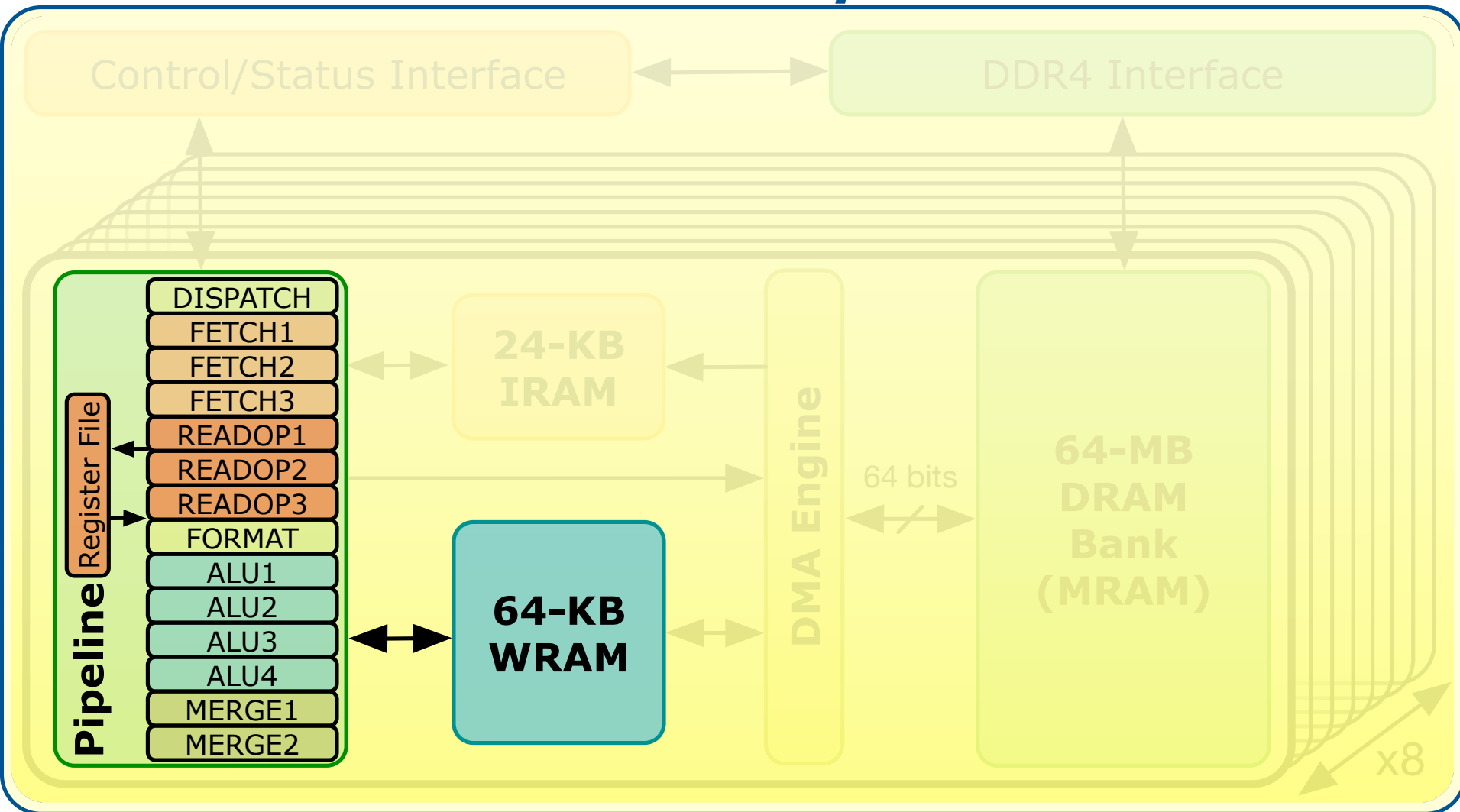
run.sh

PRIM -- first commit

9 days ago

# DPU: WRAM Bandwidth

## *PIM Chip*



# WRAM Bandwidth: Microbenchmark

---

- Goal
  - Measure the **WRAM bandwidth** for the STREAM benchmark
- Microbenchmark
  - We implement the four versions of STREAM: **COPY, ADD, SCALE, and TRIAD**
  - The operations performed in ADD, SCALE, and TRIAD are **addition, multiplication, and addition+multiplication**, respectively
  - We vary the number of tasklets from 1 to 16
  - We show results for 1 DPU
- We do *not* include accesses to MRAM

# STREAM Benchmark in WRAM

// COPY

```
for(int i = 0; i < SIZE; i++){  
    bufferB[i] = bufferA[i];  
}
```

8 bytes read, 8 bytes written,  
no arithmetic operations

// ADD

```
for(int i = 0; i < SIZE; i++){  
    bufferC[i] = bufferA[i] + bufferB[i];  
}
```

16 bytes read, 8 bytes written,  
ADD

// SCALE

```
for(int i = 0; i < SIZE; i++){  
    bufferB[i] = scalar * bufferA[i];  
}
```

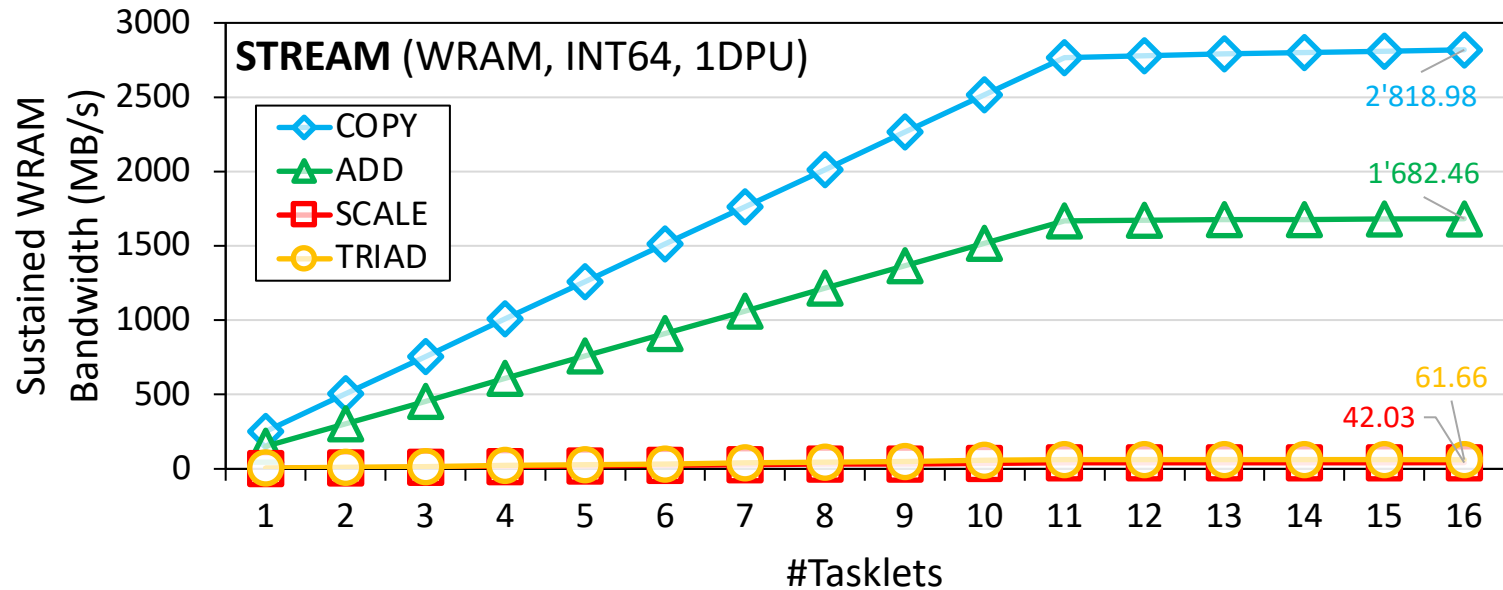
8 bytes read, 8 bytes written,  
MUL

// TRIAD

```
for(int i = 0; i < SIZE; i++){  
    bufferC[i] = bufferA[i] + scalar * bufferB[i];  
}
```

16 bytes read, 8 bytes written,  
MUL, ADD

# WRAM Bandwidth: STREAM

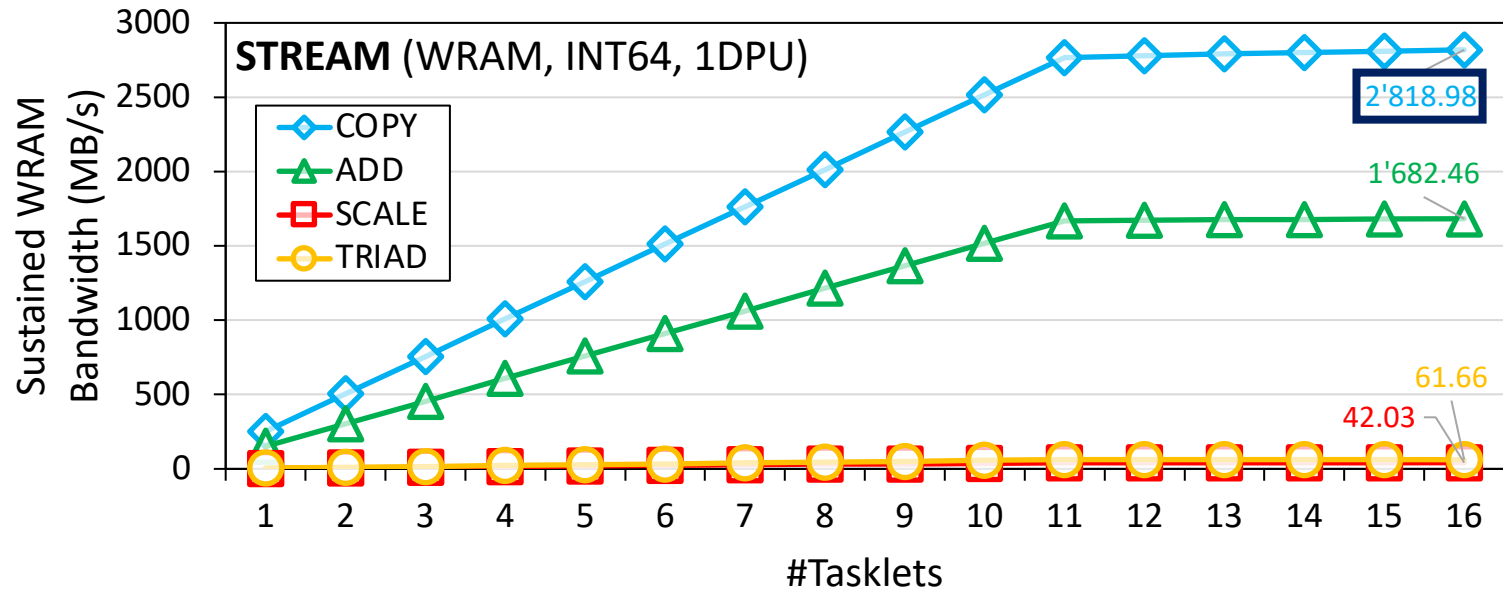


How can we estimate the bandwidth?

Assuming that the pipeline is full, and *Bytes* is the number of bytes read and written:

$$WRAM\ Bandwidth\ \left(in\ \frac{B}{S}\right) = \frac{Bytes \times frequency_{DPU}}{\#instructions}$$

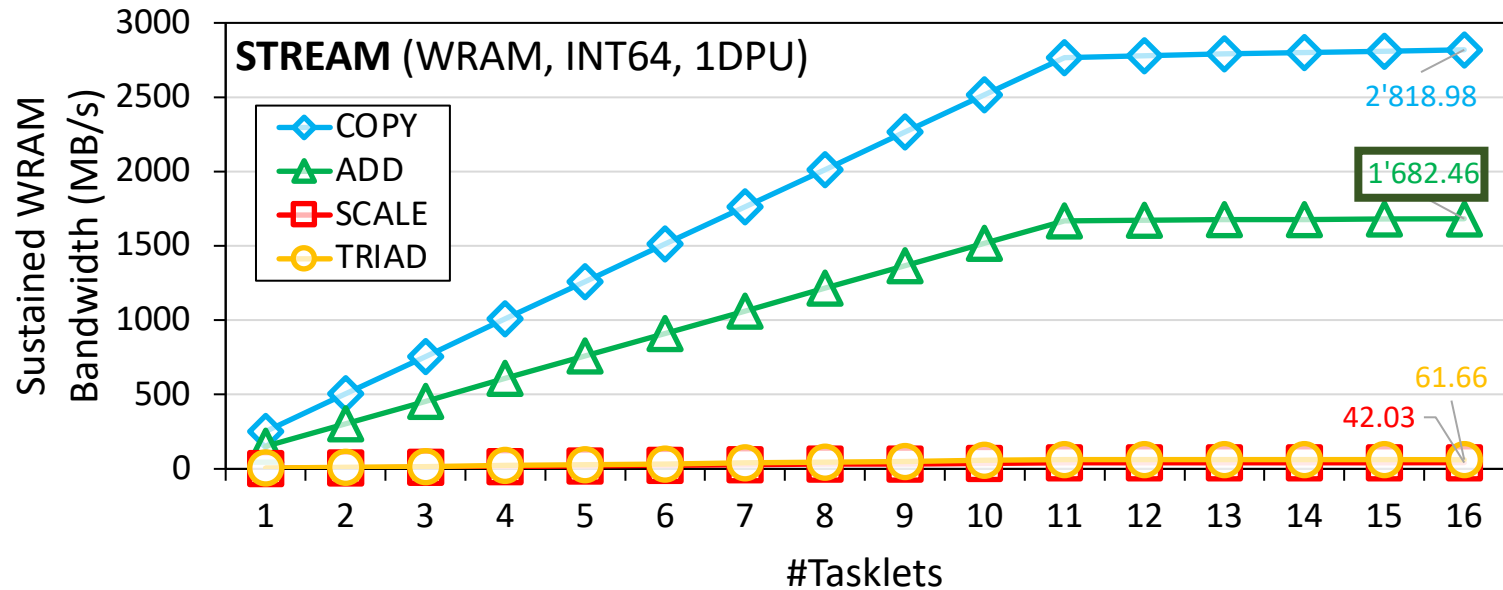
# WRAM Bandwidth: COPY



**COPY** executes **2 instructions** (WRAM load and store).  
With 11 tasklets, **11 × 16 bytes** in **22 cycles**:

$$\text{WRAM Bandwidth} \left( \text{in } \frac{B}{S} \right) = 2,800 \frac{MB}{s} \text{ at } 350 \text{ MHz}$$

# WRAM Bandwidth: ADD



$$WRAM\ Bandwidth\ \left(in\ \frac{B}{S}\right) = \frac{Bytes \times frequency_{DPU}}{\#instructions}$$

**ADD** executes 5 instructions (2 ld, add, addc, sd).  
With 11 tasklets,  $11 \times 24$  bytes in 55 cycles:

$$WRAM\ Bandwidth\ \left(in\ \frac{B}{S}\right) = 1,680 \frac{MB}{s} \text{ at } 350\ MHz$$

# WRAM Bandwidth: Access Patterns

- All 8-byte **WRAM loads and stores take one cycle** when the DPU pipeline is full

## **KEY OBSERVATION 3**

The sustained bandwidth provided by the DPU's internal Working memory (WRAM) is **independent of the memory access pattern** (either streaming, strided, or random access pattern).

**All 8-byte WRAM loads and stores take one cycle**, when the DPU's pipeline is full (i.e., with 11 or more tasklets).

- Microbenchmark: `c[a[i]]=b[a[i]];`
  - Unit-stride: `a[i]=a[i-1]+1;`
  - Strided: `a[i]=a[i-1]+stride;`
  - Random: `a[i]=rand();`



# Microbenchmark: STREAM and WRAM

- STREAM benchmark and WRAM access patterns

CMU-SAFARI / prim-benchmarks

Unwatch 2

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Makefile

PRIM -- first commit

9 days ago

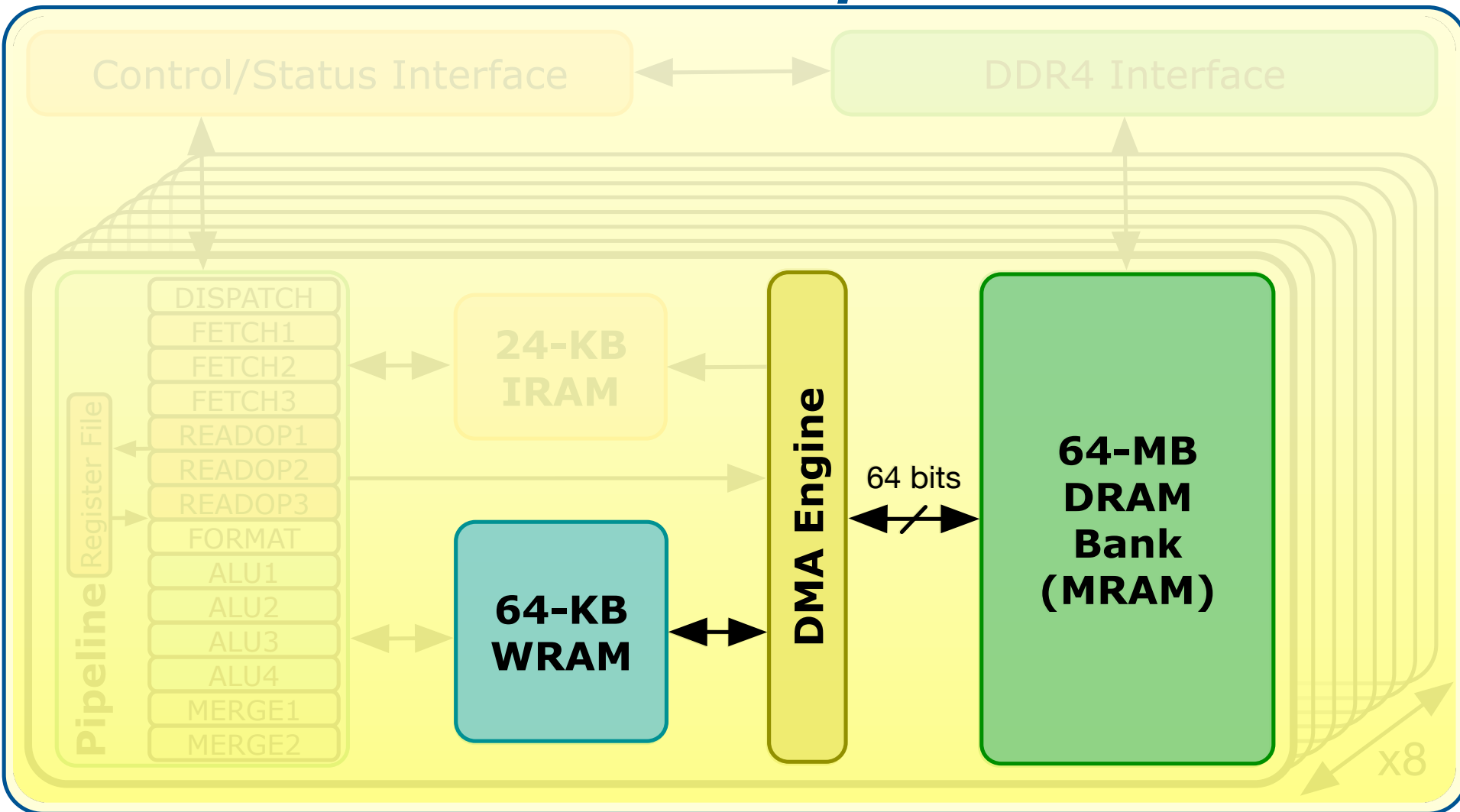
run.sh

PRIM -- first commit

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# DPU: MRAM Latency and Bandwidth

## *PIM Chip*

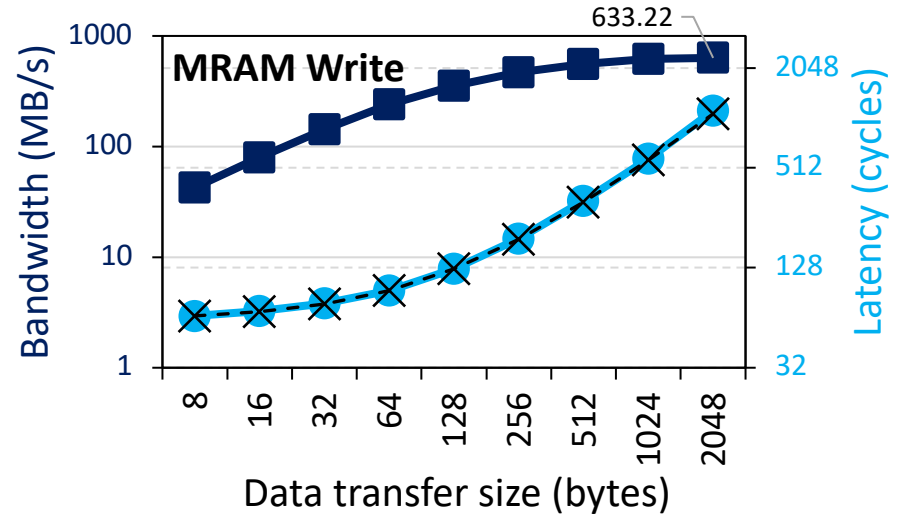
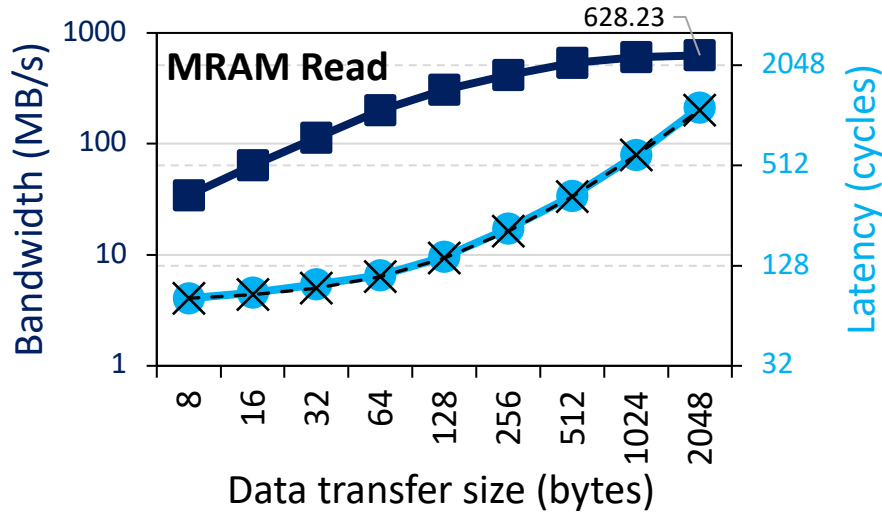


# MRAM Bandwidth

---

- Goal
  - Measure **MRAM bandwidth** for different access patterns
- Microbenchmarks
  - **Latency of a single DMA transfer** for different transfer sizes
    - `mram_read();` // MRAM-WRAM DMA transfer
    - `mram_write();` // WRAM-MRAM DMA transfer
  - **STREAM** benchmark
    - COPY, COPY-DMA
    - ADD, SCALE, TRIAD
  - **Strided** access pattern
    - Coarse-grain strided access
    - Fine-grain strided access
  - **Random** access pattern (GUPS)
- We do include accesses to MRAM

# MRAM Read and Write Latency (I)



$$MRAM \text{ Bandwidth } \left( \text{in } \frac{B}{S} \right) = \frac{\text{size} \times \text{frequency}_{DPU}}{MRAM \text{ Latency}}$$

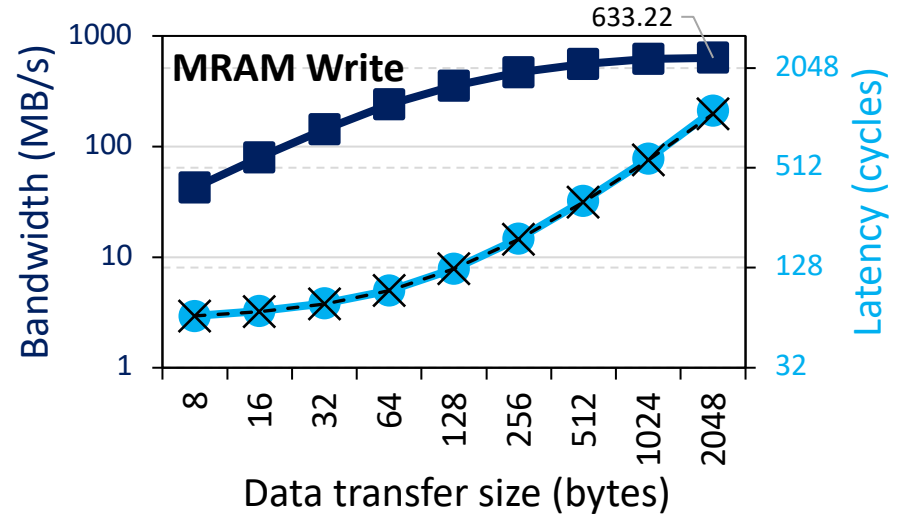
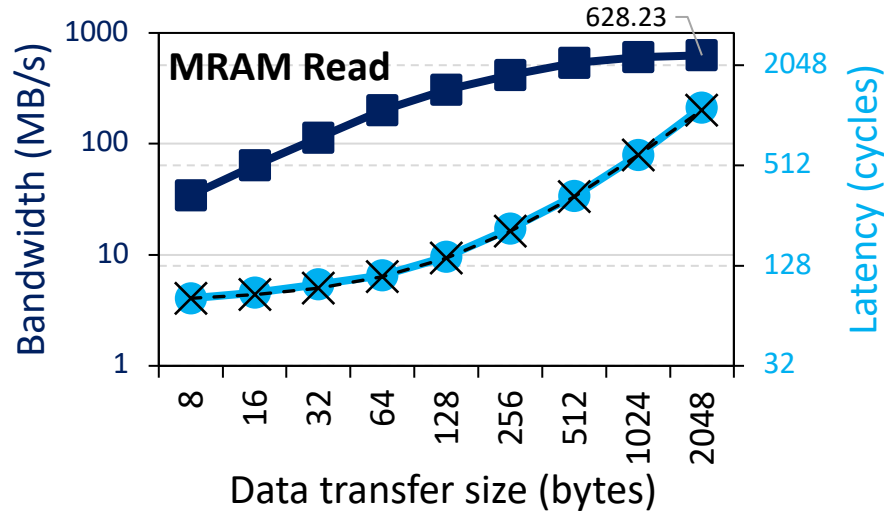
We can model the MRAM latency with a linear expression

$$MRAM \text{ Latency (in cycles)} = \alpha + \beta \times \text{size}$$

In our measurements,  $\beta$  equals 0.5 cycles/byte.

Theoretical maximum MRAM bandwidth = 700 MB/s at 350 MHz

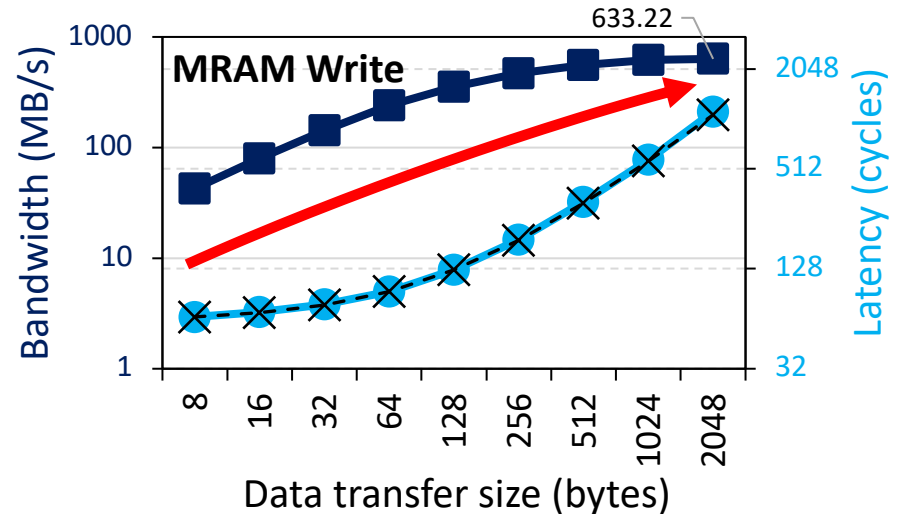
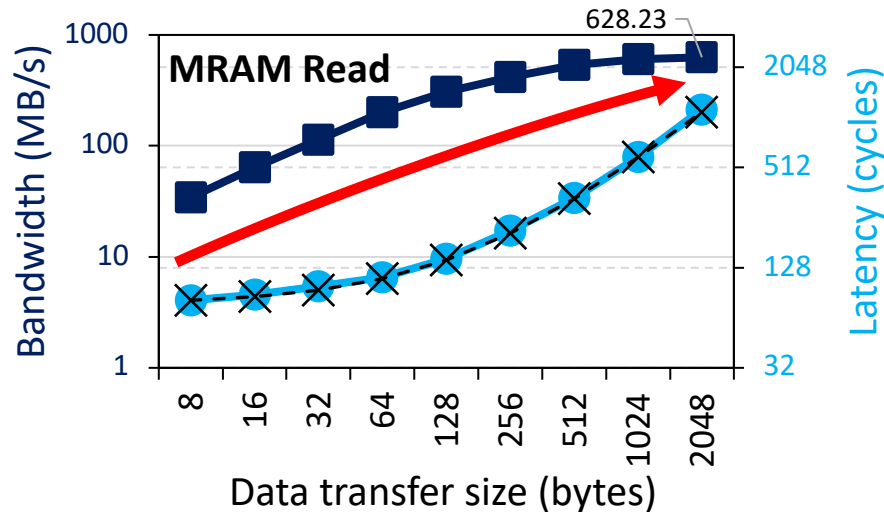
# MRAM Read and Write Latency (II)



## KEY OBSERVATION 4

- The DPU's Main memory (MRAM) bank access latency increases **linearly** with the transfer size.
- The maximum theoretical MRAM **bandwidth** is 2 bytes per cycle.

# MRAM Read and Write Latency (III)



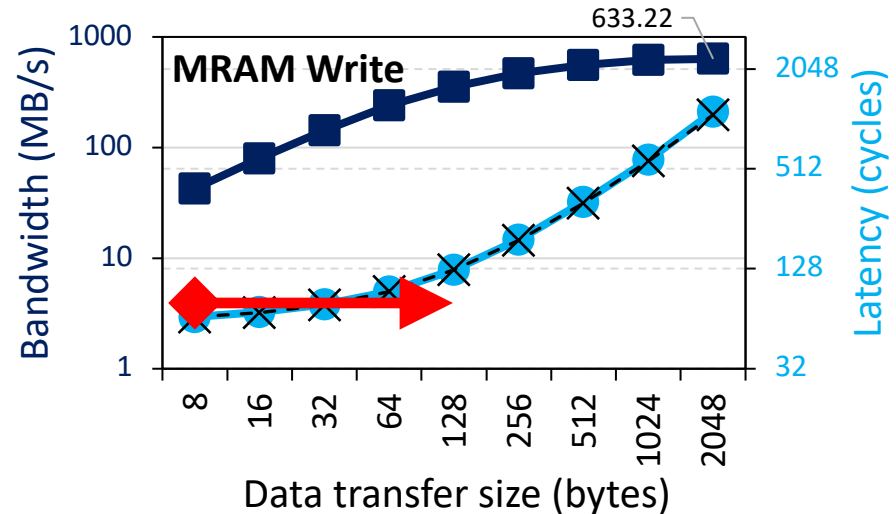
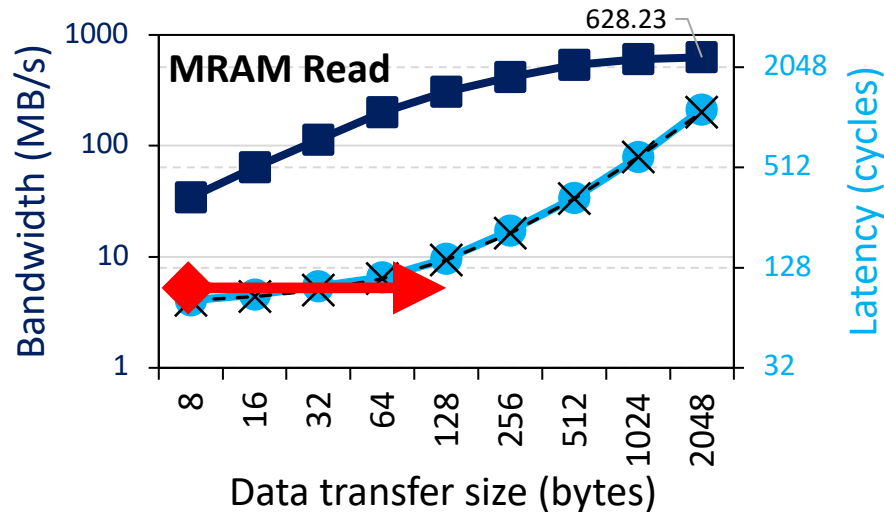
Read and write accesses to MRAM are symmetric

The sustained MRAM bandwidth increases with data transfer size

## **PROGRAMMING RECOMMENDATION 1**

For data movement between the DPU's MRAM bank and the WRAM, **use large DMA transfer sizes when all the accessed data is going to be used.**

# MRAM Read and Write Latency (IV)



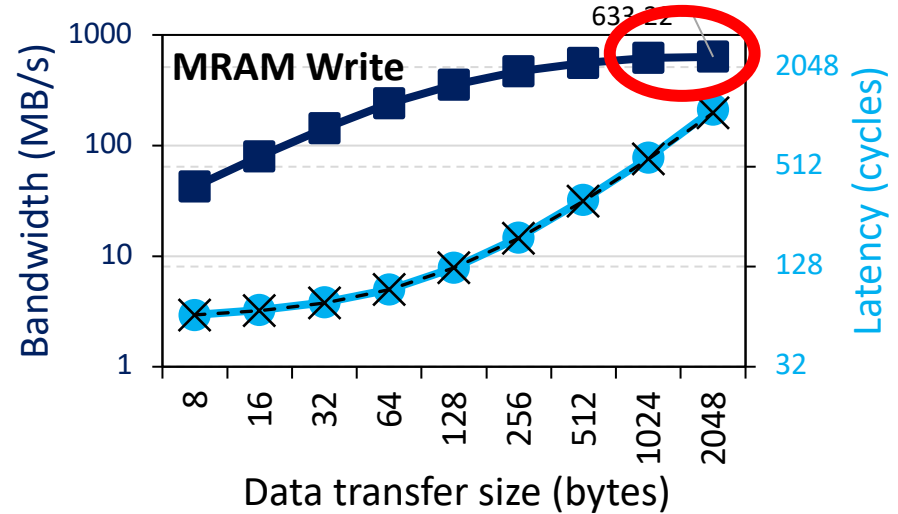
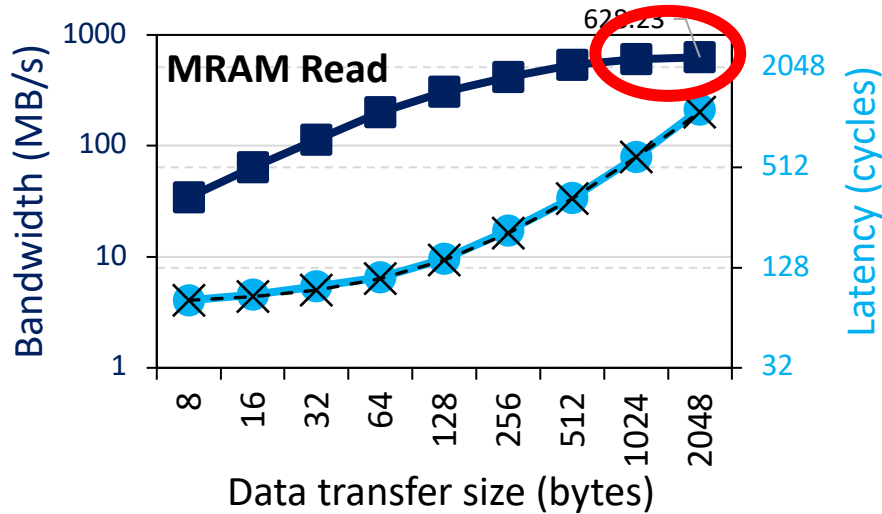
MRAM latency changes slowly between 8 and 128 bytes

For small transfers, the fixed cost ( $\alpha$ ) dominates the variable cost ( $\beta \times \text{size}$ )

## PROGRAMMING RECOMMENDATION 2

For small transfers between the MRAM bank and the WRAM, **fetch more bytes than necessary within a 128-byte limit**. Doing so increases the likelihood of finding data in WRAM for later accesses (i.e., the program can check whether the desired data is in WRAM before issuing a new MRAM access).

# MRAM Read and Write Latency (V)



2,048-byte transfers are only 4% faster than 1,024-byte transfers

Larger transfers require more WRAM, which may limit the number of tasklets

## ***PROGRAMMING RECOMMENDATION 3***

**Choose the data transfer size between the MRAM bank and the WRAM based on the program's WRAM usage**, as it imposes a tradeoff between the sustained MRAM bandwidth and the number of tasklets that can run in the DPU (which is dictated by the limited WRAM capacity).



# MRAM Bandwidth

---

- Goal
  - Measure **MRAM bandwidth** for different access patterns
- Microbenchmarks
  - **Latency of a single DMA transfer** for different transfer sizes
    - `mram_read();` // MRAM-WRAM DMA transfer
    - `mram_write();` // WRAM-MRAM DMA transfer
  - **STREAM** benchmark
    - COPY, COPY-DMA
    - ADD, SCALE, TRIAD
  - **Strided** access pattern
    - Coarse-grain strided access
    - Fine-grain strided access
  - **Random** access pattern (GUPS)
- We do include accesses to MRAM

# STREAM Benchmark in MRAM

---

```
// COPY
// Load current MRAM block to WRAM
mram_read((__mram_ptr void const*)mram_address_A, bufferA,
          SIZE * sizeof(uint64_t));

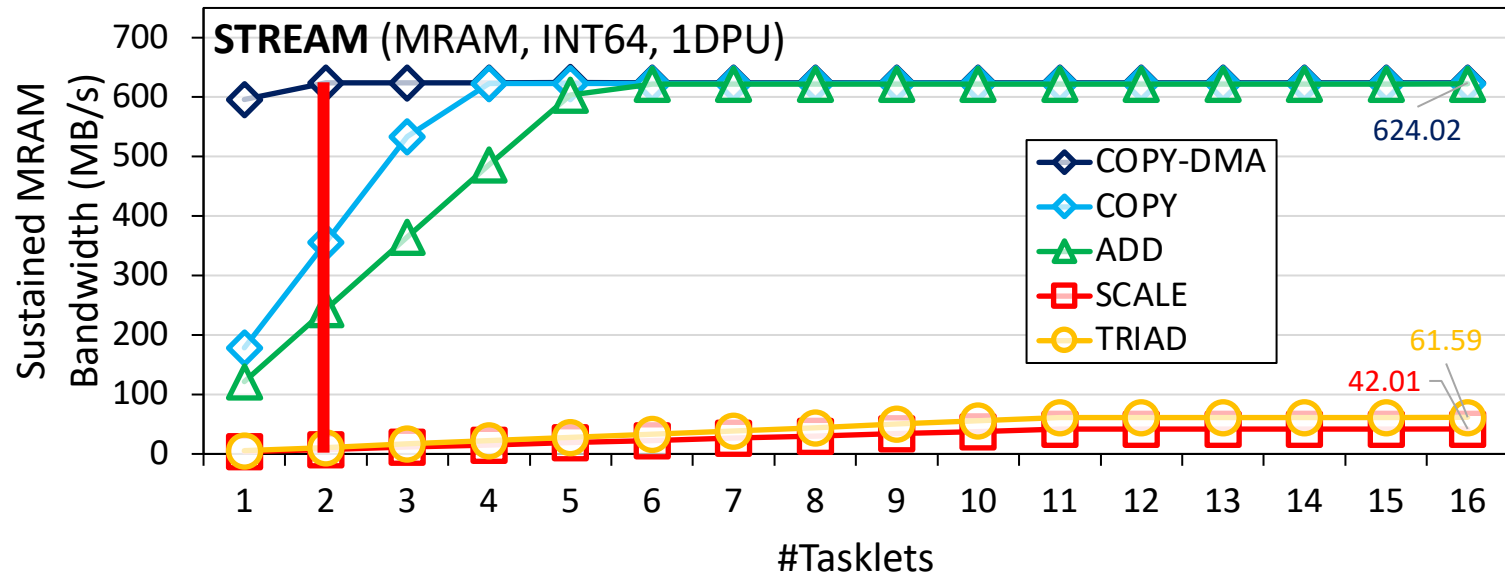
for(int i = 0; i < SIZE; i++){
    bufferB[i] = bufferA[i];
}

// Write WRAM block to MRAM
mram_write(bufferB, (__mram_ptr void*)mram_address_B,
           SIZE * sizeof(uint64_t));

// COPY-DMA
// Load current MRAM block to WRAM
mram_read((__mram_ptr void const*)mram_address_A, bufferA,
          SIZE * sizeof(uint64_t));

// Write WRAM block to MRAM
mram_write(bufferA, (__mram_ptr void*)mram_address_B,
           SIZE * sizeof(uint64_t));
```

# STREAM Benchmark: COPY-DMA

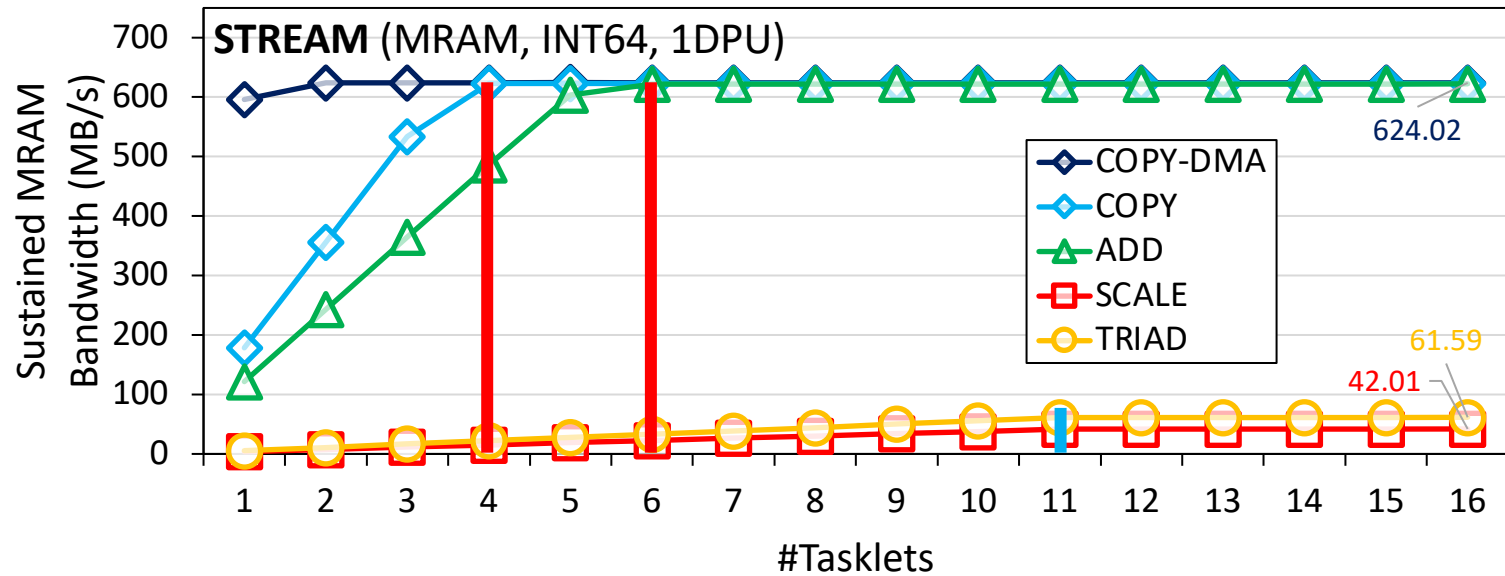


The sustained bandwidth of **COPY-DMA** is close to the theoretical maximum (700 MB/s): **~1.6 TB/s for 2,556 DPUs**

**COPY-DMA** saturates with **two tasklets**, even though the DMA engine can perform only one transfer at a time

Using **two or more tasklets** guarantees that there is always a DMA request enqueued to keep the DMA engine busy

# STREAM Benchmark: Bandwidth Saturation (I)



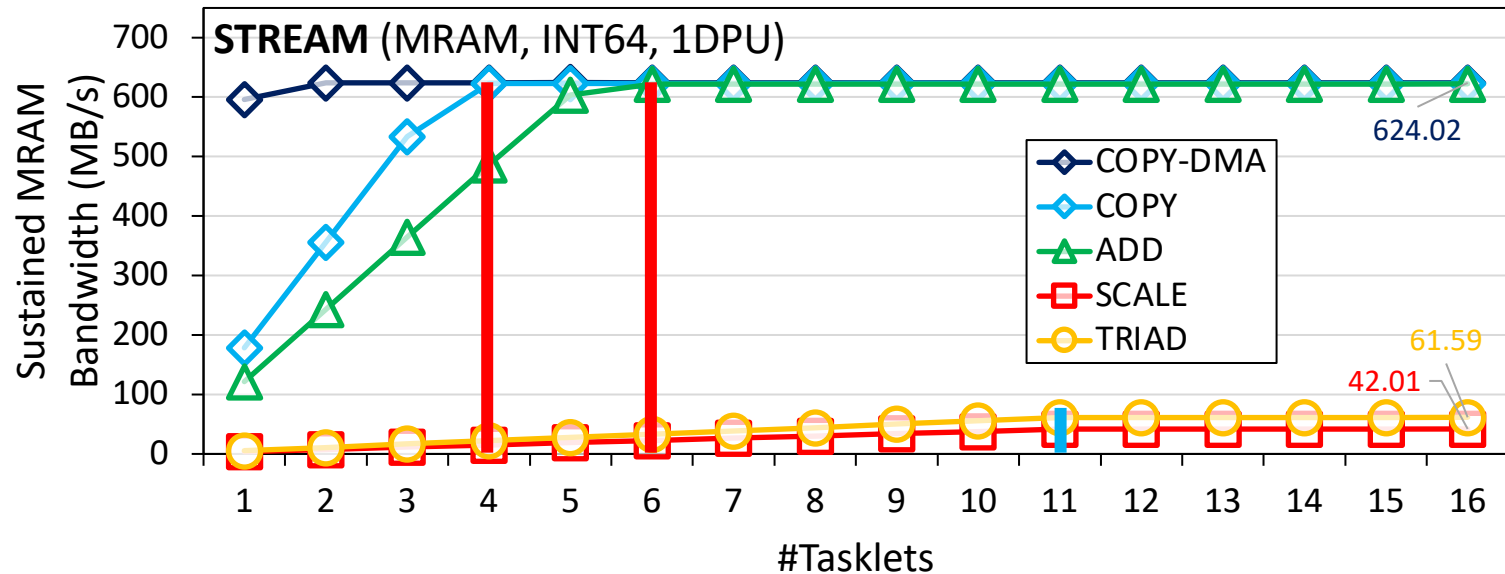
**COPY** and **ADD** saturate at 4 and 6 tasklets, respectively

**SCALE** and **TRIAD** saturate at 11 tasklets

The latency of MRAM accesses becomes longer than the pipeline latency after 4 and 6 tasklets for **COPY** and **ADD**, respectively

The pipeline latency of **SCALE** and **TRIAD** is longer than the MRAM latency for any number of tasklets (both use costly MUL)

# STREAM Benchmark: Bandwidth Saturation (II)



## KEY OBSERVATION 5

- **When the access latency to an MRAM bank for a streaming benchmark (COPY-DMA, COPY, ADD) is larger than the pipeline latency** (i.e., execution latency of arithmetic operations and WRAM accesses), the performance of the DPU saturates at a number of tasklets smaller than 11. **This is a memory-bound workload.**
- **When the pipeline latency for a streaming benchmark (SCALE, TRIAD) is larger than the MRAM access latency**, the performance of a DPU saturates at 11 tasklets. **This is a compute-bound workload.**

# MRAM Bandwidth

---

- Goal
  - Measure **MRAM bandwidth** for different access patterns
- Microbenchmarks
  - **Latency of a single DMA transfer** for different transfer sizes
    - `mram_read();` // MRAM-WRAM DMA transfer
    - `mram_write();` // WRAM-MRAM DMA transfer
  - **STREAM** benchmark
    - COPY, COPY-DMA
    - ADD, SCALE, TRIAD
  - **Strided** access pattern
    - Coarse-grain strided access
    - Fine-grain strided access
  - **Random** access pattern (GUPS)
- We do include accesses to MRAM

# Strided and Random Access to MRAM

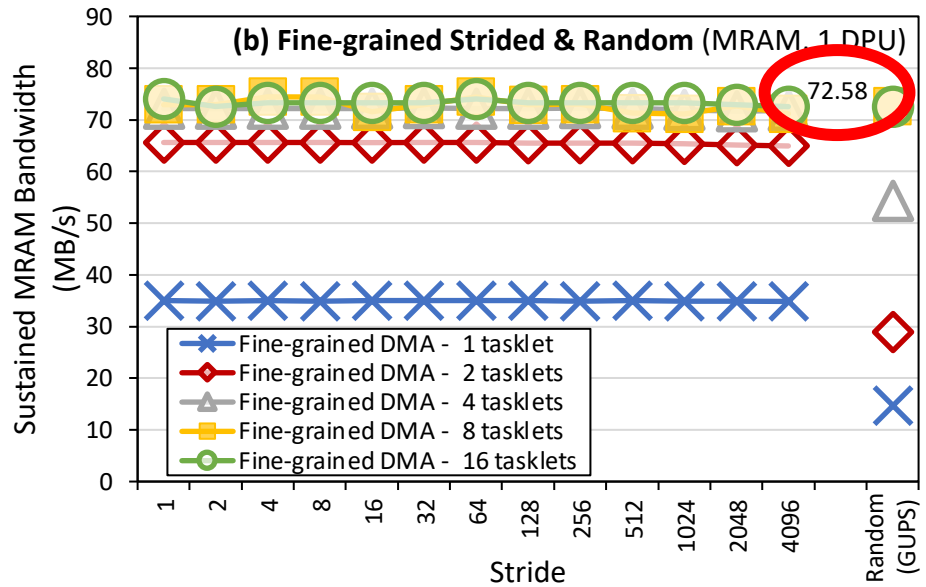
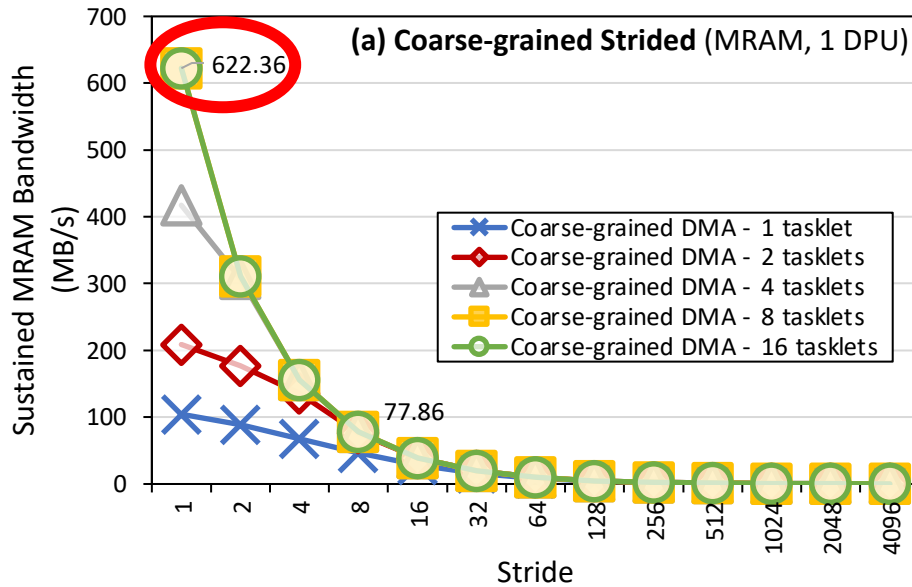
```
// COARSE-GRAINED STRIDED ACCESS
// Load current MRAM block to WRAM
mram_read((__mram_ptr void const*)mram_address_A, bufferA,
          SIZE * sizeof(uint64_t));
mram_read((__mram_ptr void const*)mram_address_B, bufferB,
          SIZE * sizeof(uint64_t));

for(int i = 0; i < SIZE; i += stride){
    bufferB[i] = bufferA[i];
}
// Write WRAM block to MRAM
mram_write(bufferB, (__mram_ptr void*)mram_address_B,
          SIZE * sizeof(uint64_t));

// FINE-GRAINED STRIDED & RANDOM ACCESS
for(int i = 0; i < SIZE; i += stride){
    int index = i * sizeof(uint64_t);
    // Load current MRAM element to WRAM
    mram_read((__mram_ptr void const*)(mram_address_A + index), bufferA,
              sizeof(uint64_t));

    // Write WRAM element to MRAM
    mram_write(bufferA, (__mram_ptr void*)(mram_address_B + index),
              sizeof(uint64_t));
}
```

# Strided and Random Accesses (I)



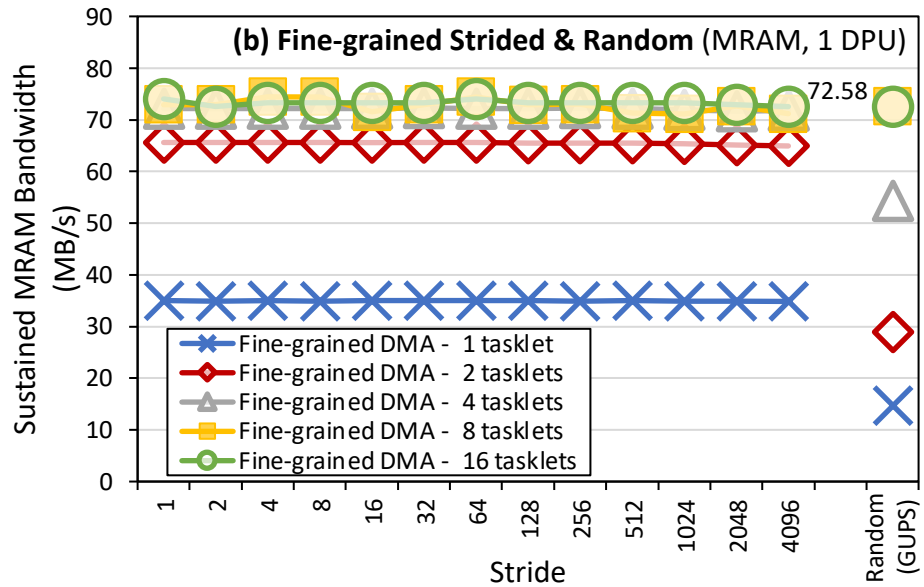
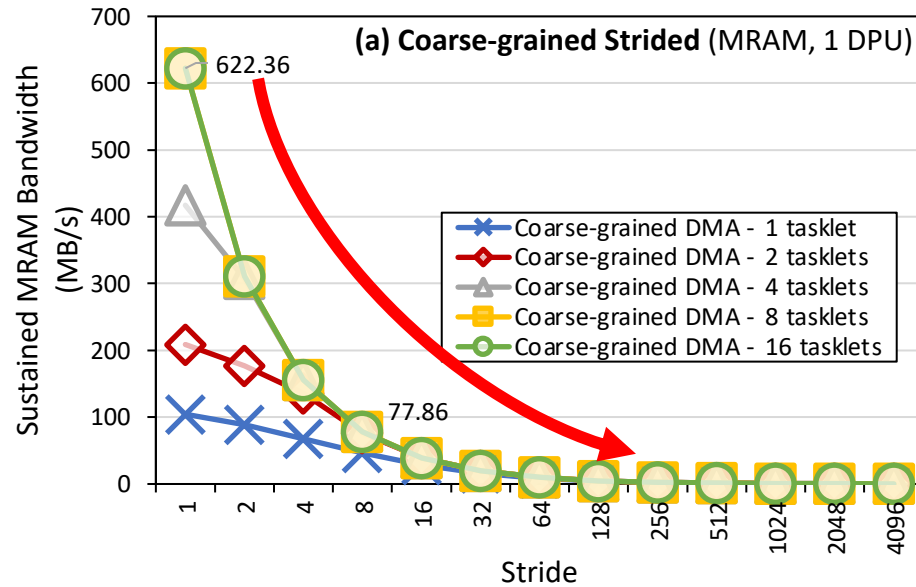
Large difference in maximum sustained bandwidth between coarse-grained and fine-grained DMA

Coarse-grained DMA uses 1,024-byte transfers, while fine-grained DMA uses 8-byte transfers

Random access achieves very similar maximum sustained bandwidth to fine-grained strided approach



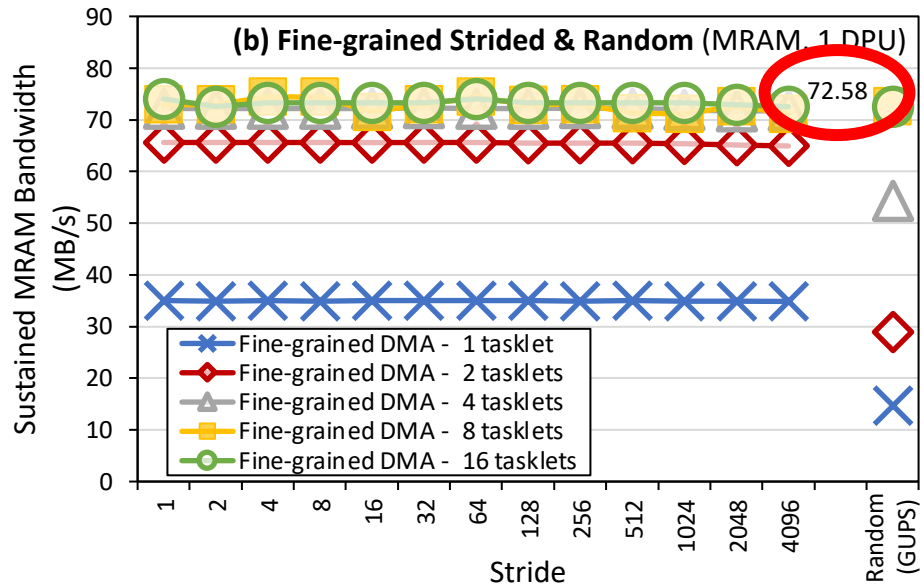
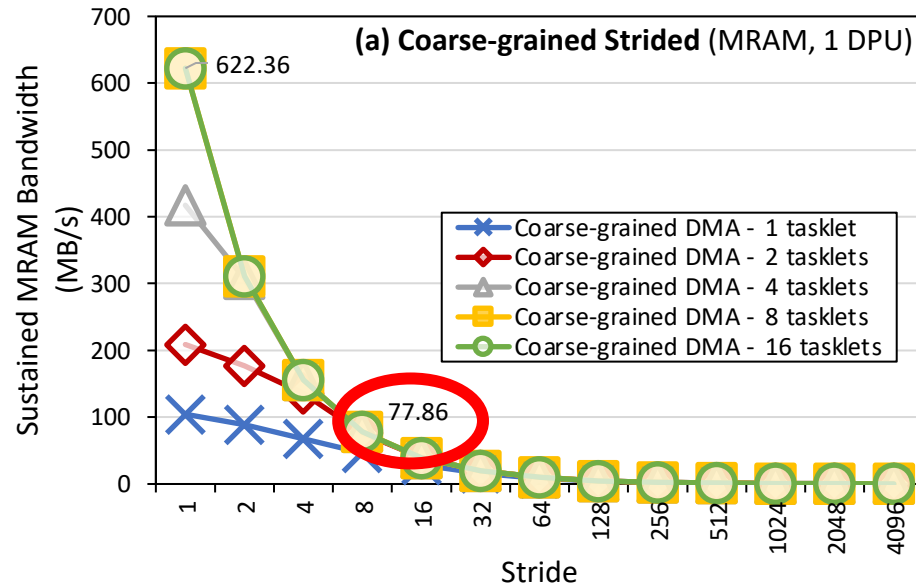
# Strided and Random Accesses (II)



The sustained MRAM bandwidth of coarse-grained DMA decreases as the stride increases

The effective utilization of the transferred data decreases as the stride becomes larger (e.g., a stride 4 means that only one fourth of the transferred data is used)

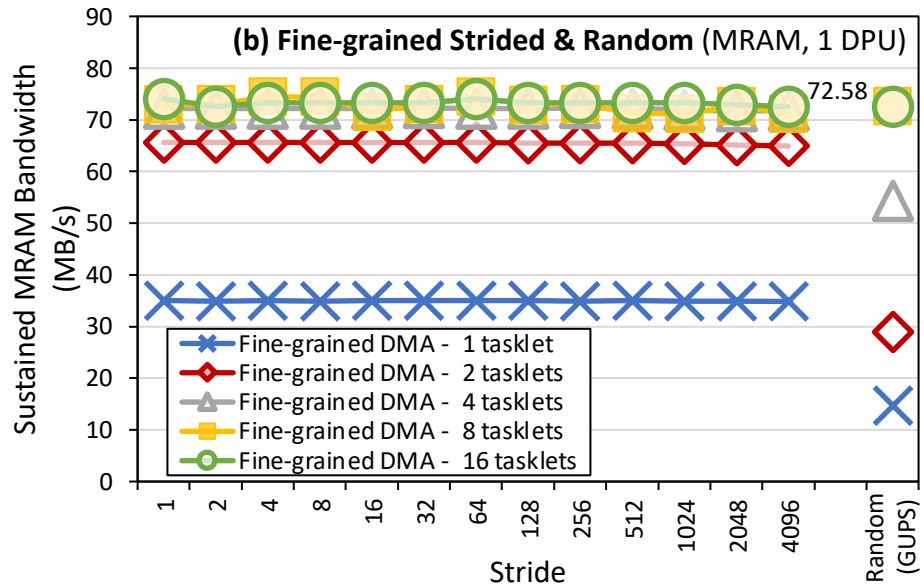
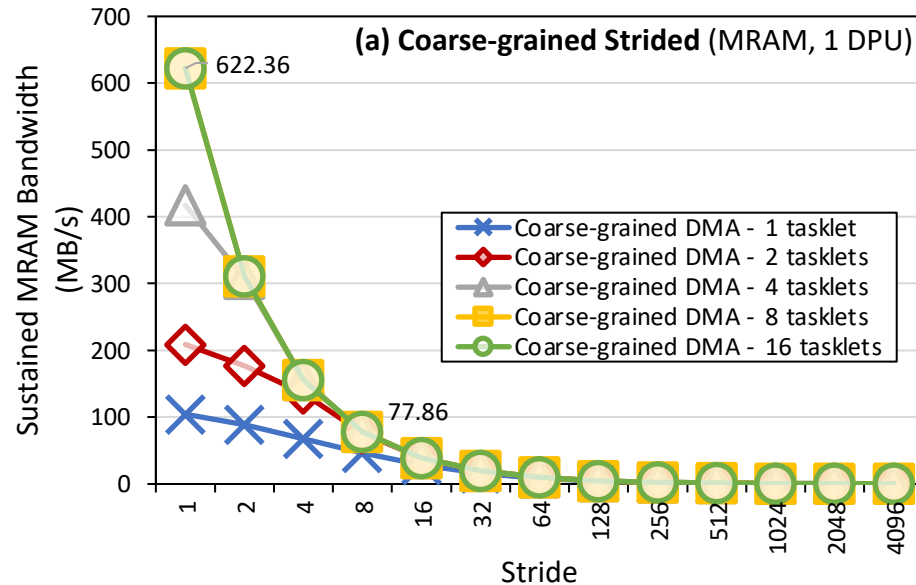
# Strided and Random Accesses (III)



For a stride of 16 or larger, the fine-grained DMA approach achieves higher bandwidth

With stride 16, only one sixteenth of the maximum sustained bandwidth (622.36 MB/s) of coarse-grained DMA is effectively used, which is lower than the bandwidth of fine-grained DMA (72.58 MB/s)

# Strided and Random Accesses (IV)




## PROGRAMMING RECOMMENDATION 4

- For strided access patterns with a **stride smaller than 16 8-byte elements**, **fetch a large contiguous chunk** (e.g., 1,024 bytes) from a DPU's MRAM bank.
- For strided access patterns with **larger strides and random access patterns**, **fetch only the data elements that are needed** from an MRAM bank.

# Microbenchmark: Strided and Random

- Strided and random accesses to MRAM

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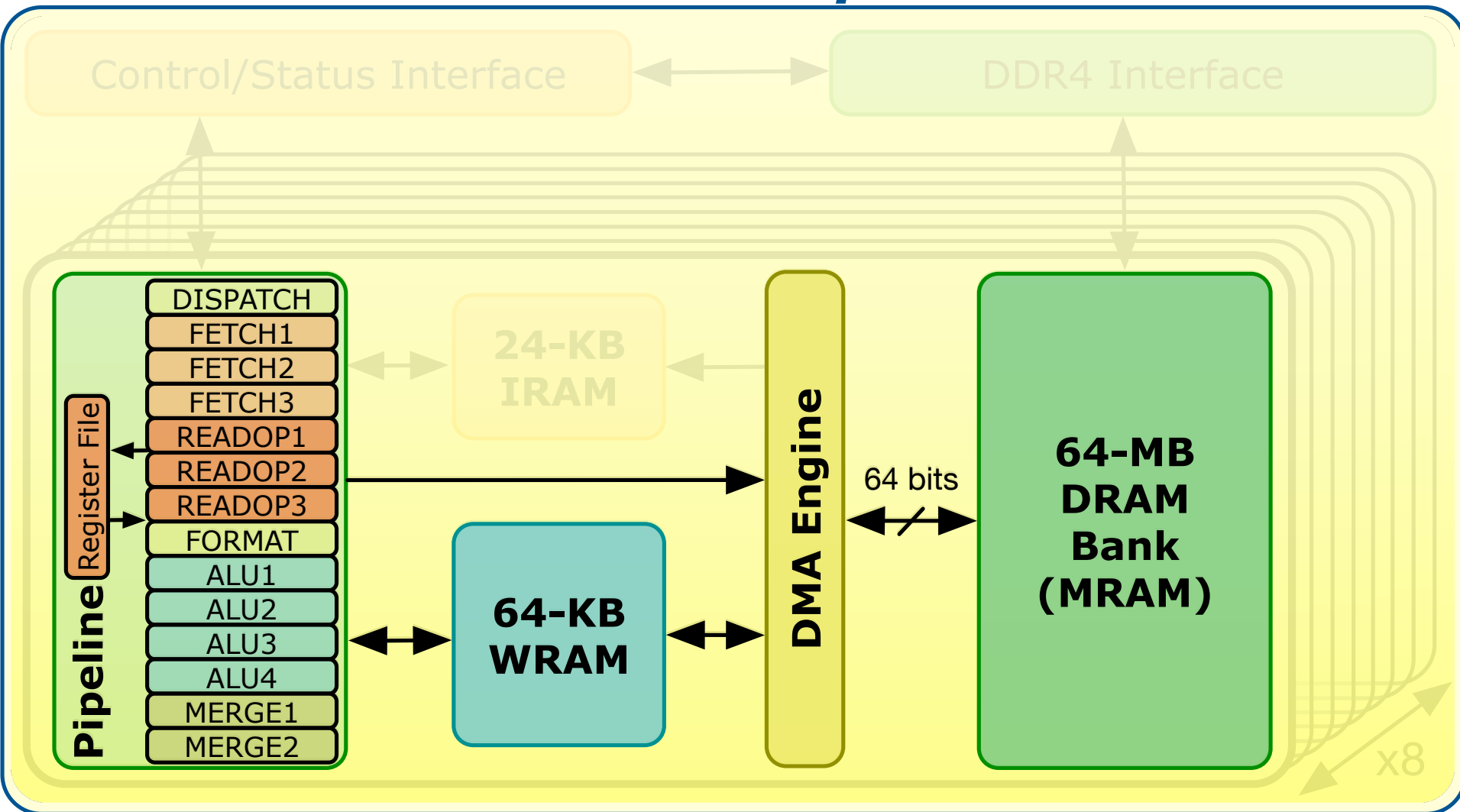
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run.sh	PRIM -- first commit	9 days ago

# DPU: Arithmetic Throughput vs. Operational Intensity

## *PIM Chip*



# Arithmetic Throughput vs. Operational Intensity (I)

---

- Goal
  - Characterize **memory-bound regions** and **compute-bound regions** for different datatypes and operations
- Microbenchmark
  - We **load one chunk of an MRAM array into WRAM**
  - Perform a **variable number of operations on the data**
  - **Write back** to MRAM
- The experiment is inspired by the **Roofline model**\*
- We define **operational intensity** (OI) as the number of arithmetic operations performed per byte accessed from MRAM (OP/B)
- The pipeline latency changes with the operational intensity, but the MRAM access latency is fixed

# Arithmetic Throughput vs. Operational Intensity (II)

```
int repetitions = input_repeat >= 1.0 ? (int)input_repeat : 1;
int stride      = input_repeat >= 1.0 ? 1 : (int)(1 / input_repeat);

// Load current MRAM block to WRAM
mram_read((__mram_ptr void const*)mram_address_A, bufferA, SIZE * sizeof(T));

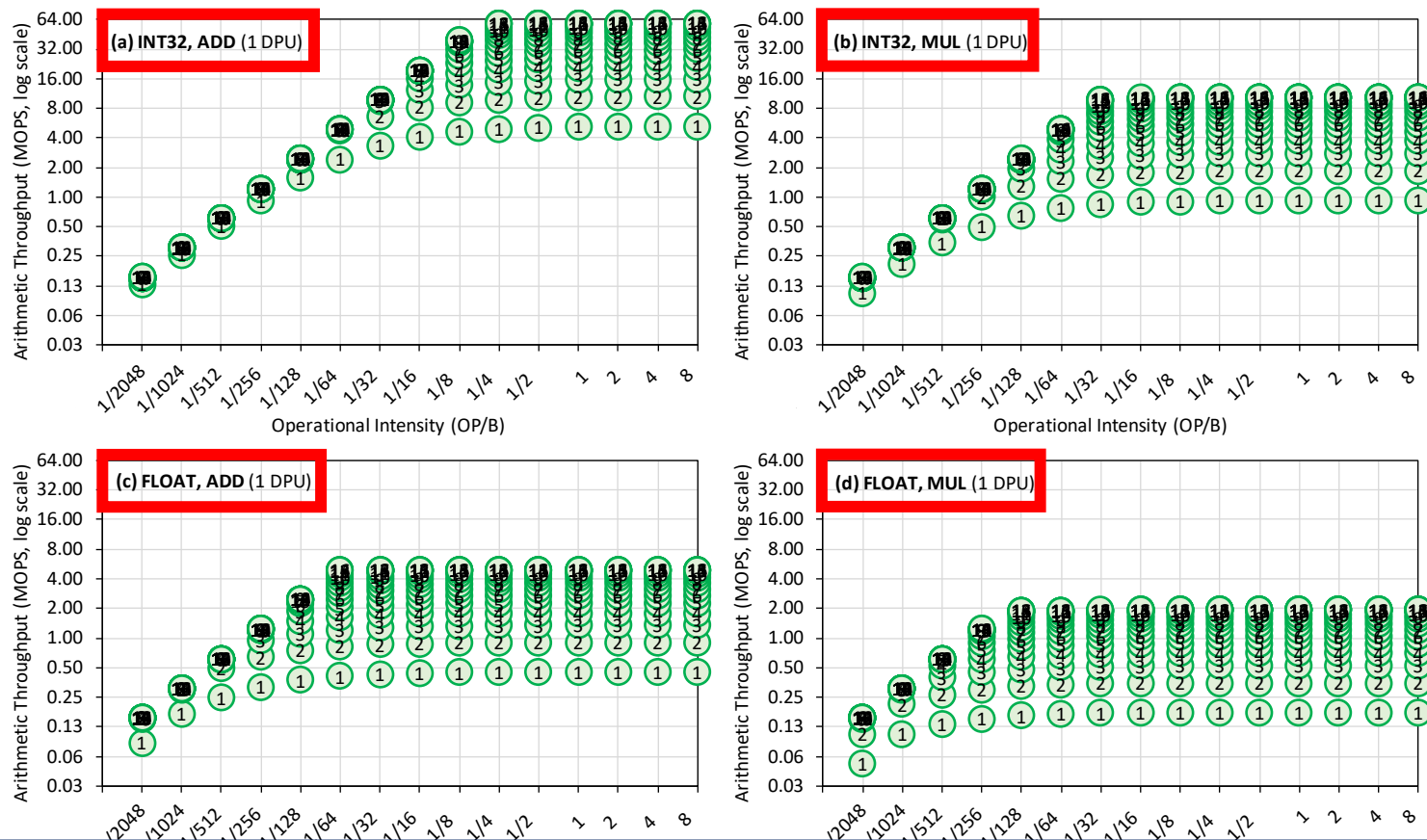
// Update
for(int r = 0; r < repetitions; r++){
    for(int i = 0; i < SIZE; i+=stride){
#ifdef ADD
        bufferA[i] += scalar; // ADD
#elif SUB
        bufferA[i] -= scalar; // SUB
#elif MUL
        bufferA[i] *= scalar; // MUL
#elif DIV
        bufferA[i] /= scalar; // DIV
#endif
    }
}

// Write WRAM block to MRAM
mram_write(bufferA, (__mram_ptr void*)mram_address_B, SIZE * sizeof(T));
```

input\_repeat greater or equal to 1 indicates the (integer) number of repetitions per input element

input\_repeat smaller than 1 indicates the fraction of elements that are updated

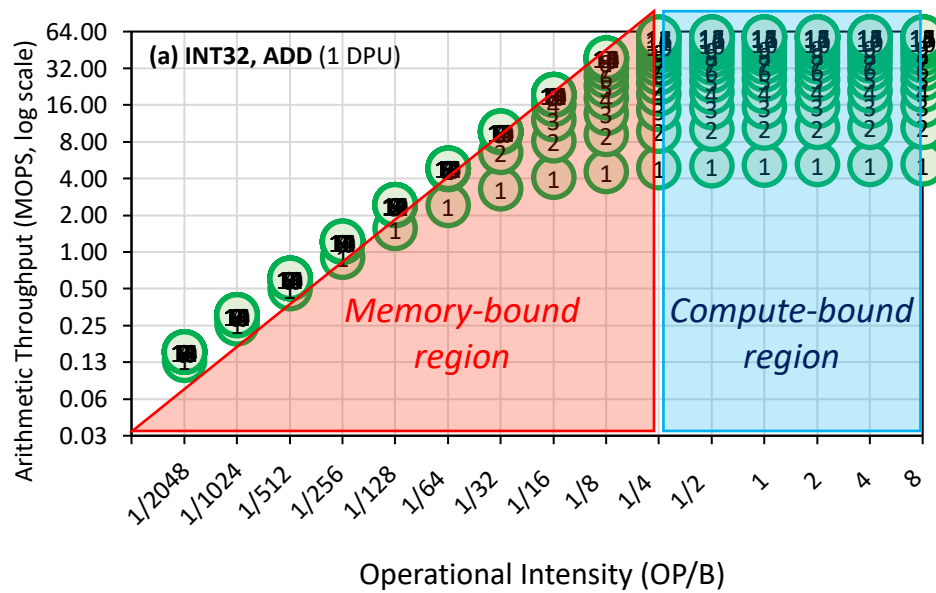
# Arithmetic Throughput vs. Operational Intensity (III)



We show results of arithmetic throughput vs. operational intensity for (a) 32-bit integer ADD, (b) 32-bit integer MUL, (c) 32-bit floating-point ADD, and (d) 32-bit floating-point MUL (results for other datatypes and operations show similar trends)



# Arithmetic Throughput vs. Operational Intensity (IV)



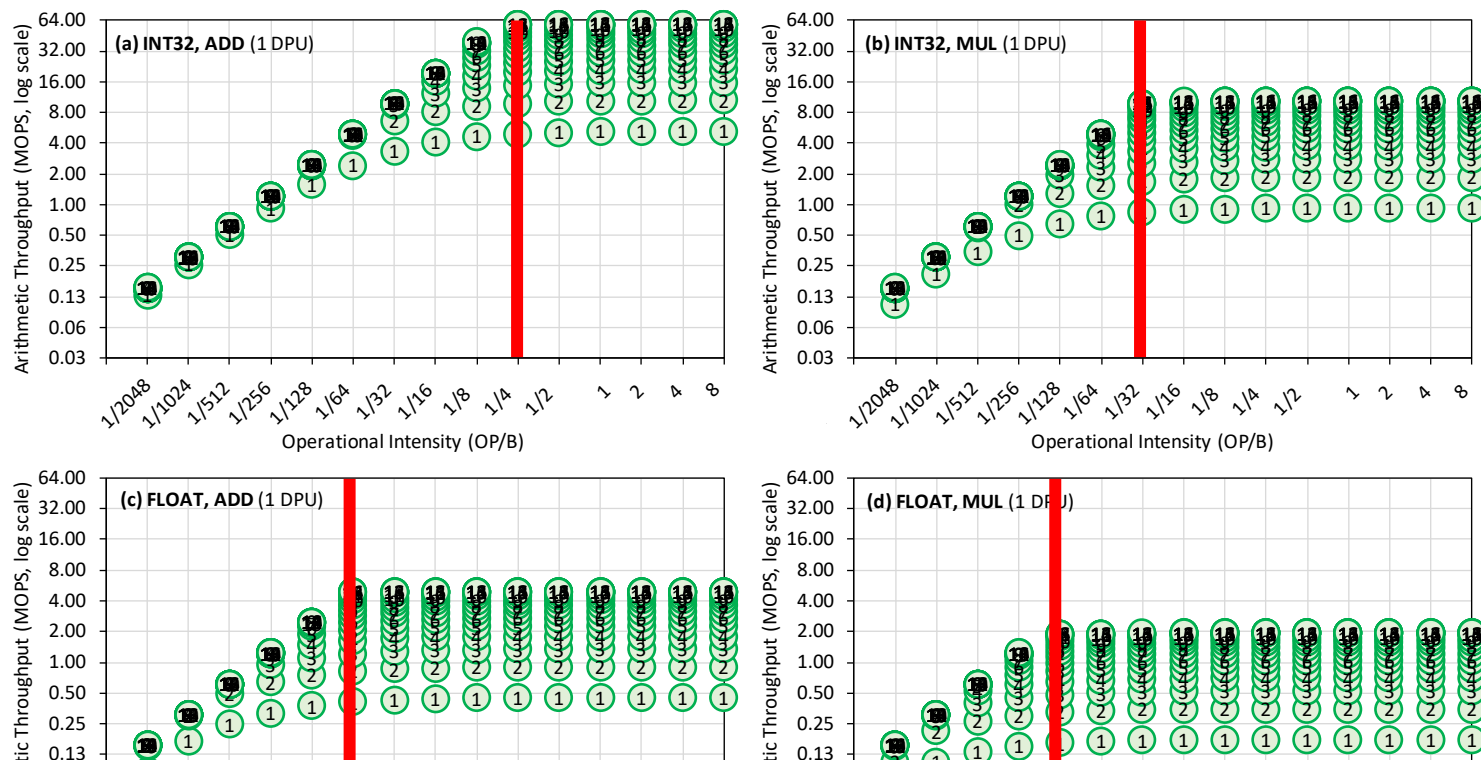
In the **memory-bound region**, the arithmetic throughput increases with the operational intensity

In the **compute-bound region**, the arithmetic throughput is flat at its maximum

The **throughput saturation point** is the operational intensity where the transition between the memory-bound region and the compute-bound region happens

The throughput saturation point is as low as  $\frac{1}{4}$  OP/B, i.e., **1 integer addition per every 32-bit element** fetched

# Arithmetic Throughput vs. Operational Intensity (V)



## KEY OBSERVATION 6

The arithmetic throughput of a DRAM Processing Unit (DPU) saturates at low or very low operational intensity (e.g., 1 integer addition per 32-bit element). Thus, the DPU is fundamentally a compute-bound processor. We expect most real-world workloads be compute-bound in the UPMEM PIM architecture.

# Microbenchmark: Arithmetic Throughput vs. Operational Intensity

- Arithmetic Throughput versus Operational Intensity

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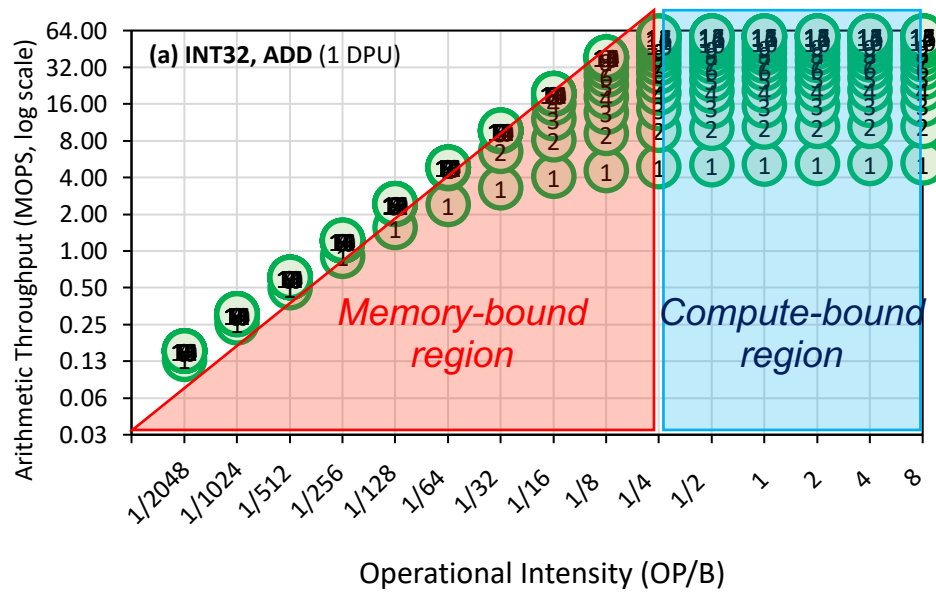
file

run.sh

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# Key Takeaway 1



The throughput saturation point is as low as  $\frac{1}{4}$  OP/B, i.e., 1 integer addition per every 32-bit element fetched

## KEY TAKEAWAY 1

The UPMEM PIM architecture is fundamentally compute bound. As a result, the most suitable workloads are memory-bound.

# Understanding a Modern PIM Architecture

---

## Benchmarking a New Paradigm: Experimental Analysis and Characterization of a Real Processing-in-Memory System

**JUAN GÓMEZ-LUNA<sup>1</sup>, IZZAT EL HAJJ<sup>2</sup>, IVAN FERNANDEZ<sup>1,3</sup>, CHRISTINA GIANNOULA<sup>1,4</sup>,  
GERALDO F. OLIVEIRA<sup>1</sup>, AND ONUR MUTLU<sup>1</sup>**

<sup>1</sup>ETH Zürich

<sup>2</sup>American University of Beirut

<sup>3</sup>University of Malaga

<sup>4</sup>National Technical University of Athens

Corresponding author: Juan Gómez-Luna (e-mail: [juang@ethz.ch](mailto:juang@ethz.ch)).

<https://arxiv.org/pdf/2105.03814.pdf>

<https://github.com/CMU-SAFARI/prim-benchmarks>

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# Experimental Analysis of the UPMEM PIM Engine

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## Benchmarking a New Paradigm: An Experimental Analysis of a Real Processing-in-Memory Architecture

JUAN GÓMEZ-LUNA, ETH Zürich, Switzerland

IZZAT EL HAJJ, American University of Beirut, Lebanon

IVAN FERNANDEZ, ETH Zürich, Switzerland and University of Malaga, Spain

CHRISTINA GIANNOULA, ETH Zürich, Switzerland and NTUA, Greece

GERALDO F. OLIVEIRA, ETH Zürich, Switzerland

ONUR MUTLU, ETH Zürich, Switzerland

Many modern workloads, such as neural networks, databases, and graph processing, are fundamentally memory-bound. For such workloads, the data movement between main memory and CPU cores imposes a significant overhead in terms of both latency and energy. A major reason is that this communication happens through a narrow bus with high latency and limited bandwidth, and the low data reuse in memory-bound workloads is insufficient to amortize the cost of main memory access. Fundamentally addressing this *data movement bottleneck* requires a paradigm where the memory system assumes an active role in computing by integrating processing capabilities. This paradigm is known as *processing-in-memory* (PIM).

Recent research explores different forms of PIM architectures, motivated by the emergence of new 3D-stacked memory technologies that integrate memory with a logic layer where processing elements can be easily placed. Past works evaluate these architectures in simulation or, at best, with simplified hardware prototypes. In contrast, the UPMEM company has designed and manufactured the first publicly-available real-world PIM architecture. The UPMEM PIM architecture combines traditional DRAM memory arrays with general-purpose in-order cores, called *DRAM Processing Units* (DPUs), integrated in the same chip.

This paper provides the first comprehensive analysis of the first publicly-available real-world PIM architecture. We make two key contributions. First, we conduct an experimental characterization of the UPMEM-based PIM system using microbenchmarks to assess various architecture limits such as compute throughput and memory bandwidth, yielding new insights. Second, we present *PrIM* (*Processing-In-Memory benchmarks*), a benchmark suite of 16 workloads from different application domains (e.g., dense/sparse linear algebra, databases, data analytics, graph processing, neural networks, bioinformatics, image processing), which we identify as memory-bound. We evaluate the performance and scaling characteristics of PrIM benchmarks on the UPMEM PIM architecture, and compare their performance and energy consumption to their state-of-the-art CPU and GPU counterparts. Our extensive evaluation conducted on two real UPMEM-based PIM systems with 640 and 2,556 DPUs provides new insights about suitability of different workloads to the PIM system, programming recommendations for software designers, and suggestions and hints for hardware and architecture designers of future PIM systems.



# Understanding a Modern PIM Architecture



The image shows a YouTube video player interface. The video title is "Understanding a Modern Processing-in-Memory Architecture: Benchmarking and Experimental Characterization". The speaker is Juan Gómez Luna, Izzat El Hajj, Ivan Fernandez, Christina Giannoula, Geraldo F. Oliveira, and Onur Mutlu. The video is from the channel "Onur Mutlu Lectures" and has 18.7K subscribers. The video is a live stream from July 12, 2021, with 2,579 views. The video player shows the title, speaker names, and links to the arXiv paper and GitHub repository. The video player also shows the ETH Zürich and SAFARI logos. The video player controls are visible at the bottom, including a progress bar, play/pause button, volume, and full screen button. The video player also shows the channel name "Onur Mutlu Lectures" and the number of subscribers "18.7K subscribers". The video player also shows the number of likes "93" and the number of comments "0". The video player also shows the "SHARE" button and the "SAVE" button. The video player also shows the "SUBSCRIBED" button and the notification bell icon.

**Understanding a Modern Processing-in-Memory Architecture: Benchmarking and Experimental Characterization**

Juan Gómez Luna, Izzat El Hajj,  
Ivan Fernandez, Christina Giannoula,  
Geraldo F. Oliveira, Onur Mutlu

<https://arxiv.org/pdf/2105.03814.pdf>  
<https://github.com/CMU-SAFARI/prim-benchmarks>

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# Upcoming Lectures

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- Introduction to Samsung's and SK Hynix's PIM devices
- Programming an UPMEM-based PIM system
- Workload characterization for PIM suitability



# P&S Processing-in-Memory

Real-World Processing-in-Memory Architectures:  
Microbenchmarking of UPMEM PIM

Dr. Juan Gómez Luna

Prof. Onur Mutlu

ETH Zürich

Fall 2022

1 November 2022